nd Construction of Large-Panel
e Structures

tal Report B "Horizontal Joint Tests"

DESIGN AND CONSTRU
LARGE PANEL CONCRETE STR

Contr

supplemer

Horizontal Jo

No

FOREWORD

Traditionally, multi-story buildings are so cons
that if a load-carrying member collapses, the entire
structure does not: it has an inherent structural in
But construction using large-panel concrete members i
not traditional. Builders cannot necessarily depend
the new structure's inherent integrity.

To avoid potential problems, the Office of Polic
Development and Research has undertaken an extensive
research program on large-panel concrete structures.
report, the sixth of nine, deals with horizontal join
tests, and most importantly with the connection of
walls to floors.

The research program was supervised for HUD by t
late William J. Werner and continued by Ronald J. Mor
Designers, manufacturers, and builders have reason to
grateful to them.

Donna E. Shalala
Assistant Secretary for Polic
Development and Research

LIST OF ILLUSTRATIONS

ABSTRACT

This report describes full-scale tests conducted on horizontal investigate the behavior of wall-to-floor connections in la structures. Splitting tests were also made to determine the optim of reinforcement in the ends of the walls to limit splitting. variables included in the test program were strength of grout in t amount of transverse wall reinforcement, and presence of appl moment and rotation. Effects of test variables on joint strength cussed and a design procedure is proposed.

experimental report on horizontal joints is part of a series of
ng to the development of a "Methodology for the Design and Cons
rge Panel (LP) Structures." The objective of the tests descr
report was to investigate the behavior of interior and exterior
connections in LP structures.

en full-scale joint tests and seven splitting tests were made.
mens consisted of an assembly of precast hollow-core floor sl
st concrete wall elements forming a wall-to-floor connectio
mens represented a short length of wall from a large panel b
was used to fill the joint between the ends of the floor slabs.
on of vertical load through the joint was investigated by apply
compressive force in increments.

simplified splitting tests were made on specimens consistir
wall element loaded to represent partial surface loading pre
oint. The objective was to determine the optimum amount of tr
orcement in the ends of the wall panels to limit splitting.

xperimental program included the following controlled test varia

- strength of grout in the joint,
- amount of transverse wall reinforcement,
- filled or unfilled slab cores, and
- applied floor moment and rotation.

essive strength of concrete used in the wall panels and the
w-core slab elements was held constant.

ding upon the provided combination of test variables mention
ollowing damage patterns were observed at ultimate load:

- grout crushing,
- wall splitting, and
- slab crushing.

the presence of transverse wall reinforcement increased overall st
the connection. The optimum amount of wall reinforcement dep
strength of grout in the joint. With low-strength grouts, the joint
was increased substantially by filling the slab cores with grout in
nection region. However, in the case of high-strength grouts, fi
cores was only effective if the wall panels were adequately r
against splitting.

The following conclusions are based on results of the experimental p

1. Joint capacity increases with grout compressive streng
joint strength is controlled by grout crushing.

2. Wall splitting does not occur when low-strength grout is us

3. For unreinforced walls, as the grout strength approaches
pressive strength, the mode of joint behavior changes f
crushing to wall splitting. Therefore, grout strengths hi
wall strengths do not increase joint capacity unless the
adequately reinforced. The amount of wall reinforcement
to prevent splitting increases with grout strength.

4. Filling slab cores with grout directly affects joint stre
low strength grouts are used. However, when medium or high
grouts are used, filled cores are effective only if the wa
are reinforced.

5. Inadequate dry packing below the upper wall panel leads
stantial loss of joint strength.

6. Floor moment and rotation do not have a significant effect
capacity.

various design methods to determine the load capacity of horizont
are discussed. A new design procedure is proposed. Comparisons o
and calculated strengths for various joint specimens are made.

In addition, details of the experimental program and properties of
in the joints, are included as appendices to the report.

Detailed recommendations for specific analysis and design of conne
presented in Report 5.

rm "large panel" (LP) concrete structure is used to describe a s
system composed of precast vertical wall panels with precast floor
of panels or planks assembled as shown in Fig. 1. These prefabri
ent buildings can be considered to be the industrialized form of
nal cast-in-place structural wall (egg crate) construction.
buildings are differentiated by the general arrangement of load-be
as shown in Fig. 2:

) Cross wall system: in this most prevalent form, load-bearing
walls are perpendicular to the longitudinal axis of the buildin

) Spine wall system: for this form load-bearing walls are par
to the longitudinal axis of the structure.

) Mixed systems: a combination of cross wall and spine wall sy
is used.

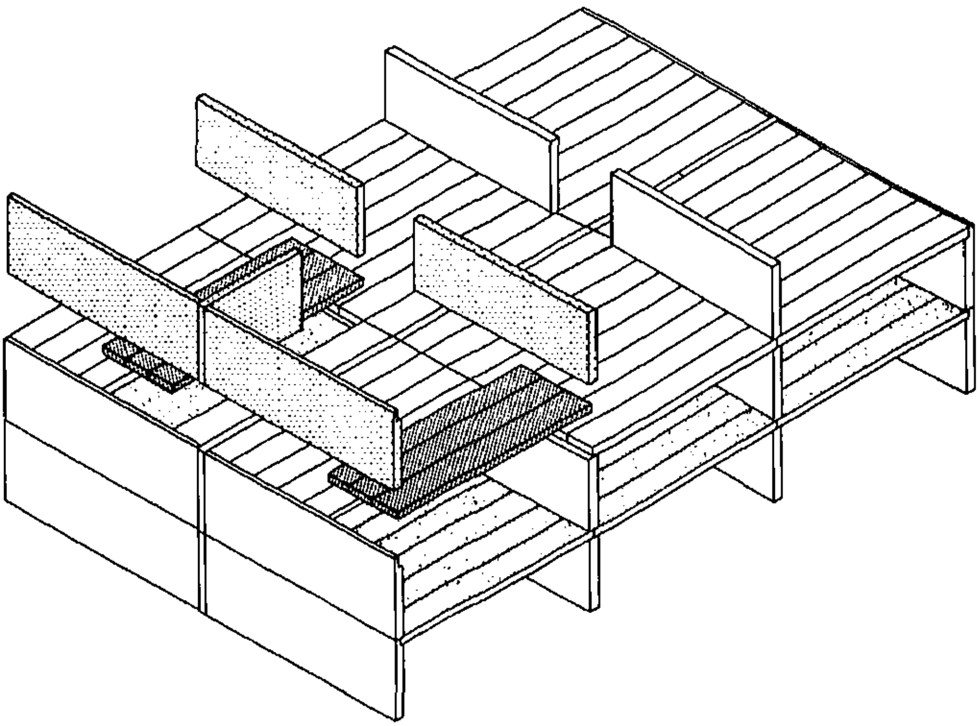
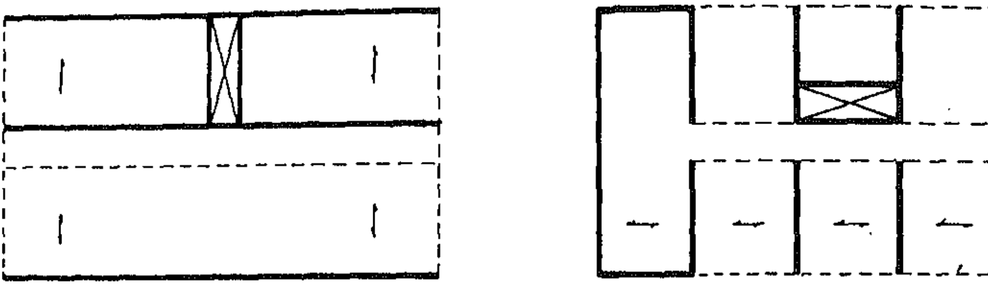


Fig. 1 Isometric View of Idealized Large Panel Structure



(a) Cross Wall System (b) Spine Wall System

Fig. 2 Idealized Plan Arrangement of Structural Wall Panels in
Panel Structures

In most LP systems, the walls transfer their loads directly to the subs
ture without an intermediate frame. This form of construction restricts
plans at any level. Thus it is most typically suited for multistory ho
where walls have to be provided between apartments to resist fire and
transmission. Construction types considered under this investigative pr
include solid, sandwich, ribbed, hollow core or composite wall p
Solid, hollow core, or ribbed floor units with or without cast-in-plac
ping are also included. All elements can be either prestressed or c
tionally reinforced.

The overall program objective is to develop minimum criteria for the
and construction of large panel structures. These criteria are being
oped to ensure structural safety and serviceability of LP residential
ings, while also providing minimum performance requirements to be us
designers and developers of innovative systems. Development of the cr
will also expand the knowledge of design and construction of large
structures to a level comparable with that existing for conventional ca
place concrete or steel structural systems.

n a structural viewpoint, the essential difference between a cast-in crete structure and a precast large panel structure is the nature c tions between elements. The function of connections is to transfer n one element to another. Ability of large panel structures to p isfactorily under all conditions of loading depends upon the integr connections. Connections must transmit gravity loads from floor t ments, from wall to wall, and from wall elements to the foundation. t also provide for interaction between the various elements and fo ient ductility in resisting lateral loads. If the connections are e, strength of the adjoining elements may not be fully utilized.

nections may be classified [1] as interior horizontal wall-to- erior horizontal wall-to-floor, horizontal floor-to-floor, and ve -to-wall. The main objective of the tests described in this repo investigate behavior of wall-to-floor connections commonly used ed States. The report covers tests of both interior and exterior tal joints. A single configuration of "Platform Joints" was t pressive strength of concrete in wall panels and hollow-core slab ength of dry-packed mortar below the upper wall panel were held co oughout the test series.

cific analysis and design techniques for types of connections co d in LP structures, are presented in Report 5[2].

Details of the test spe

Figs. 3 and 4, respectively. Controlled variables included in

gram were:

(a) strength of grout in the joint,

(b) amount of transverse reinforcement at the top and b

panels,

(c) filled or unfilled slab cores, and

(d) applied floor moment and rotation.

Design compressive strength of concrete used in the wall p

precast floor slab elements was about 5000 psi (34.5 MPa).

2.1 Test Specimens

Sixteen full-scale wall-to-floor connections and seven s

splitting specimens were tested. In the connection tes

elements consisted of precast concrete hollow-core

elements were blocks of precast concrete. Nominal thick

of floor planks were 8 in. (203 mm) and 24 in. (610 mm), r

Detailed descriptions of materials, specimen fabricatio

tion, and test procedures are given in Appendix C.

2.1.1 Specimen JM-1

Before beginning the main test program, Specimen JM-

determine the influence of applied floor moment and

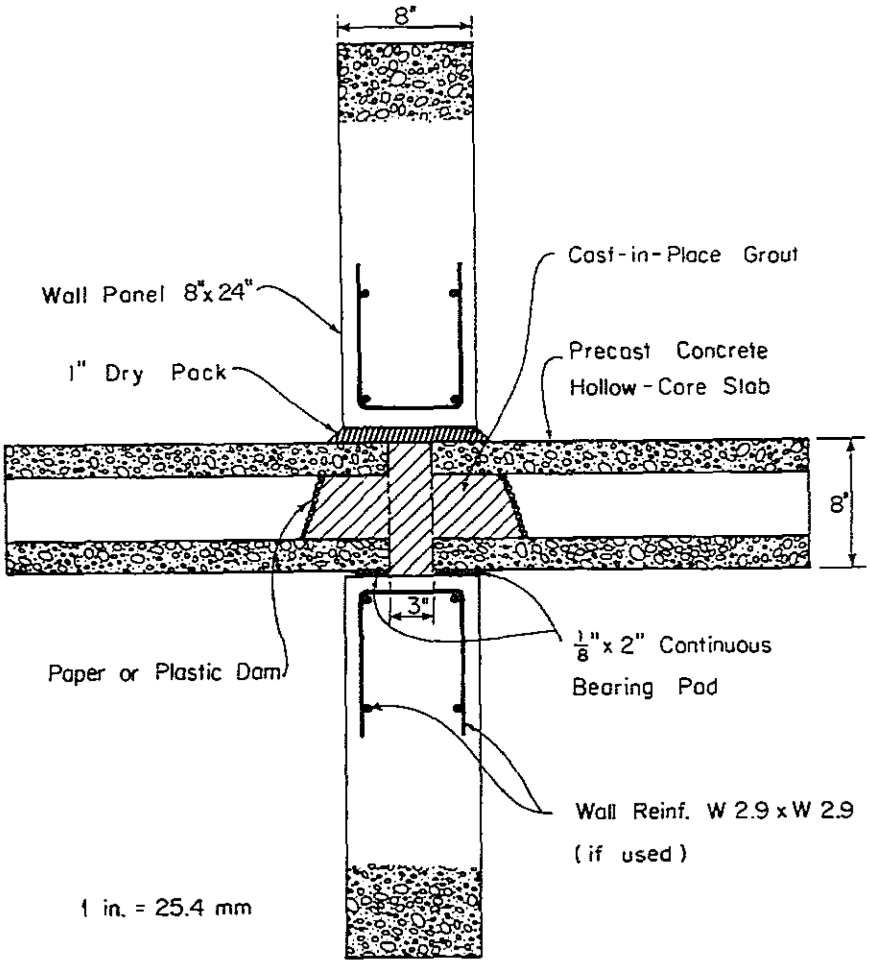
on joint strength. The test was performed using

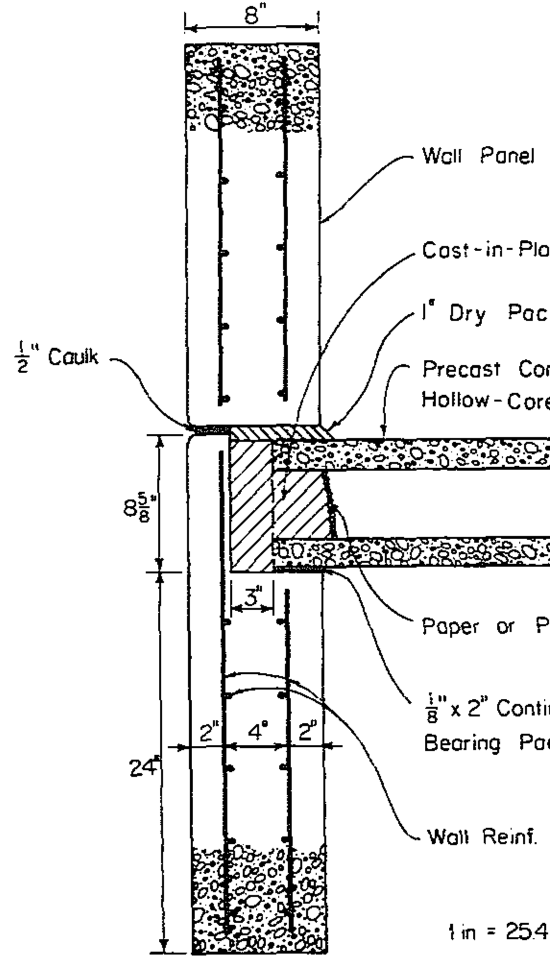
long slabs on each side of the connection. Test se

arrangement are shown in Fig. 5. Vertical load was

wall in increments by a hydraulic testing machi

rams[3] were used to apply floor moment by appl


8"
Wall Panel 8"x 24"
1" Dry Pack
Cast-in-Place Grout
Precast Concrete
Hollow-Core Slab
8"
3"
Paper or Plastic Dam
1/8" x 2" Continuous
Bearing Pad
Wall Reinf. W 2.9 x W 2.9
(if used)
1 in. = 25.4 mm


8"
1/2" Caulk
8 5/8"
3"
2"
4"
2"
24"

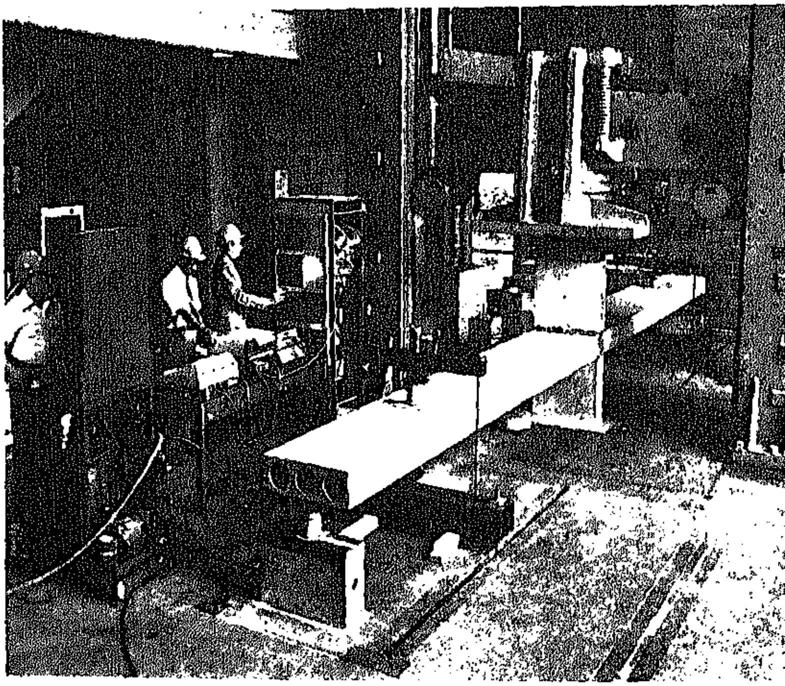


Fig. 5 Test Setup for Specimen JM-1

increased. The load on the slabs was measured by a pa
cells[4].

Negative moment introduced at the joint was slightly les
calculated cracking moment for a 24-in. (0.61 m) wide un
slab. Each floor load was positioned at about the third
the simply supported end of the slab. This provided a
shear ratio of about 5 at the joint. The figure was based
lations for a 30-ft. (9.14 m) long slab, assumed fixed at

For Specimen JM-1, grout strength was 3000 psi (20.7 M
top and bottom walls were unreinforced.

2.1.2 Series A - Splitting Tests

Splitting tests were performed to determine the optimum
transverse reinforcement needed in the ends of the wall
splitting. Wall blocks were plastered to the base of t
machine. Vertical load was applied on top through a 3-i
wide by 24-in. (610 mm) long steel plate. This loading
responded to the area loaded by the grout column in
joint. Figure 6 shows the test setup for this series.
compressive strength and amount of reinforcement provide
specimen in this series are shown in Table 1.

2.1.3 Series J and B - Interior Joint Tests

Ten tests were conducted in Series J and B. Figure 7 show
setup. A comparison of test results from trial Specimen
J-1 indicated that applied floor moment and rotation did
joint strength. Consequently, short slabs, without ar
floor moment, were used for the remaining tests. However
blocks were supported at the free ends to prevent rotation

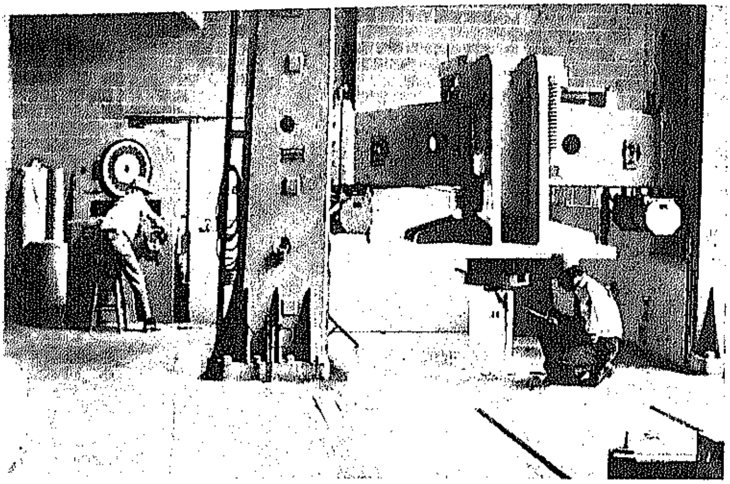


Fig. 6 Splitting Wall Test Setup

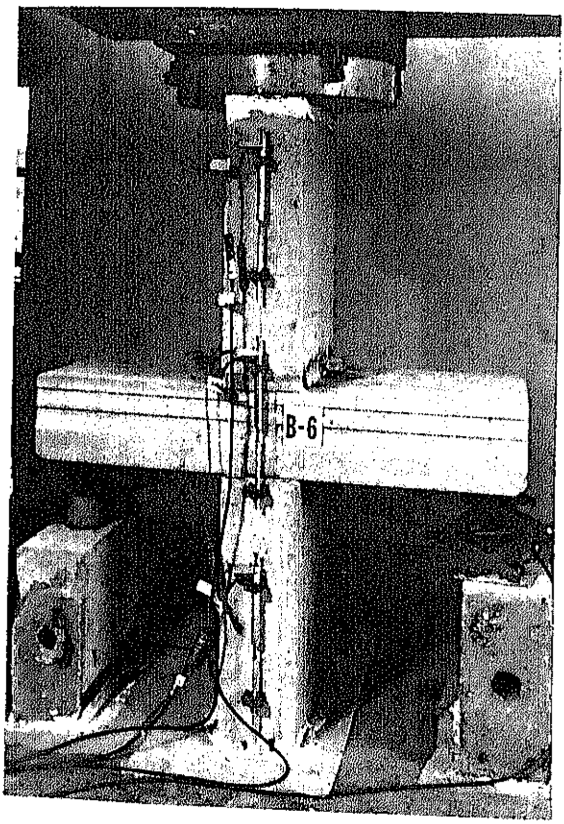


Fig. 7 Interior Joint Test Setup

Specimen Number	Concrete Strength* (psi)	Amount of Wall Reinforcement (in.^{2})	Size of Welded Wire Fabric**	Number of Wires
A-1	5040	0	0	0
A-2	4910	0.041	6x6 - W2.1xW2.1	2
A-7	5040	0.082	6x6 - W2.1xW2.1	4
A-3	5040	0.116	6x6 - W2.9xW2.9	4
A-4	4910	0.144	6x6 - W2.1xW2.1	7
A-5	4910	0.227	6x6 - W2.1xW2.1	11
A-6	4910	0.309	6x6 - W2.1xW2.1	15

*Average compressive strength measured on six 6x12-in. cylinders.

**6x6-in. mesh with W2.1 and W2.9 wires corresponds to diameters of 0.162 and 0.192 in., respectively.

Metric equivalents: 1 psi = 6.89 kPa
1 in. = 25.4 mm

Controlled test variables were:

(a) strength of grout in the joint,

(b) amount of transverse wall reinforcement, and

(c) filled or unfilled slab cores.

Grout strength, amount of wall reinforcement and other detai
different interior joint tests are given in Table 2.

2.1.4 Series E - Exterior Joint Tests

Details of exterior joint test specimens are shown in Fig. 4.
full-scale tests were conducted. Controlled variables inclu
the test program were similar to those for interior joints
test setup is illustrated in Fig. 8. The layout of instrumen
was similar to the interior joints.

Grout strength, amount of wall reinforcement and other det
exterior joints are given in Table 3.

Specimen Number	Concrete Strength* (psi)	Grout Strength* (psi)	Amount of Wall Reinf.** (in.^{2})	Slab Cores Filled or Unfilled	
JM-1***	4860	3000	0	Filled	Po Dr
J-1	4860	3000	0	Filled	
B-6	5380	2730	0	Unfilled	
B-7	5380	3240	0.116	Unfilled	
B-5	5420	2980	0	Filled	
B-2	5310	3260	0.116	Filled	
B-3A	4810	4510	0.116	Unfilled	
J-2	4820	5000	0	Filled	
J-3	4820	5000	0.116	Filled	
B-4	5310	6800	0.116	Filled	
B-1	4810	4510	0.116	Filled	

*Average compressive strength measured on nine 6x12-in. cylinders.

*6x6-W2.9xW2.9, four cross wires per wall, A_s = 4x0.029 = 0.116 in.

*Specimen with long slabs and applied floor moment.

Metric Equivalents: 1 psi = 6.89 kPa.
1 in = 25.4 mm

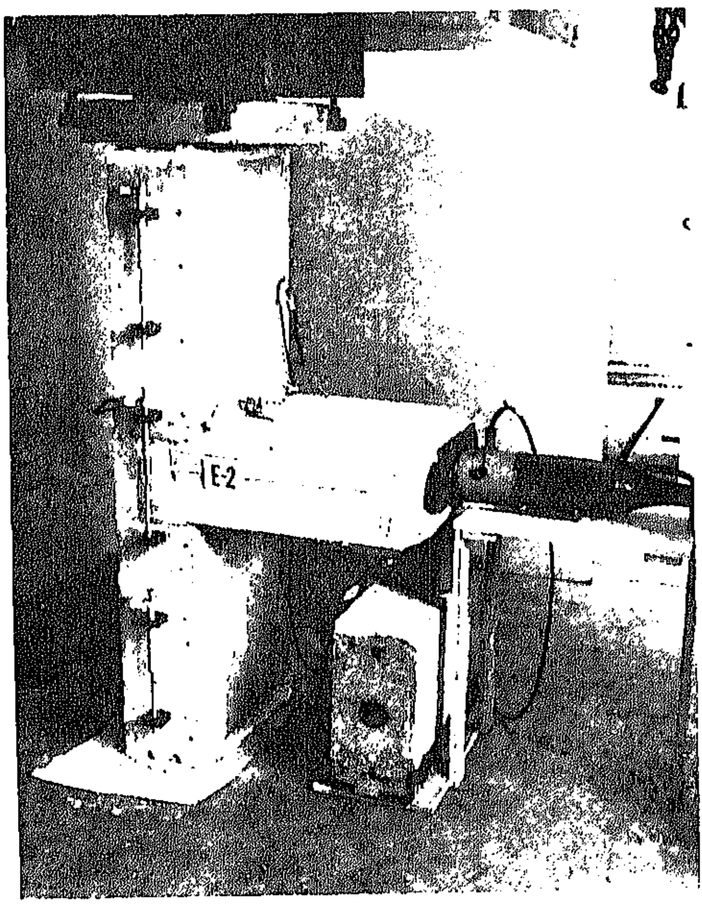


Fig. 8 Exterior Joint Test Setup

Specimen Number	Concrete Strength* (psi)	Grout Strength* (psi)	Amount of Wall Reinf.** (in.^{2})	S
E-1	5420	2980	0	
E-2	5180	2840	0	
E-3	5180	4770	0	
E-4	4900	4630	0	
E-5	4900	4510	0.116	

*Average compressive strength measured on six 6x12-in. cyl

**6x6-W2.9xW2.9, four cross wires per wall panel, A_s = 4x0.

Metric Equivalents: 1 psi = 6.89 kPa
1 in. = 25.4 mm

.1 Specimen Strength

easured ultimate loads and relevant data are listed in Table 4. onvenience, these results are expressed both as ultimate load, nd as average wall stress. The latter was obtained by dividing ltimate load by the bearing area of the wall panel. Also give able 4 are the behavior observations at ultimate load. These iscussed further in Section 3.3.

easured values of the ultimate load versus wall reinforcement for plitting test series are shown in Fig. 9. The minimum amount of orcement to give slightly higher ultimate load in splitting tests etermined as 0.116 in.^{2} (75 mm^2). This reinforcement was ufficient to limit wall splitting in the subsequent joint tests ow to medium strength grouts were used.

.2 Joint Shortening

ariation of vertical shortening, top wall horizontal strain, and ontal crack widths with applied loads for Specimen J-2 are show igs. 10, 11, and 12, respectively. Average vertical strain for nd wall panels was calculated by dividing the total shortening, red using LVDT's[3] by the 10 in. (254 mm) gage length. Plots ther tests showed similar trends.

oint shortening is due to compression of the grout column and the ent end of each of the floor slabs. Grout strength had a major i nce on the amount of shortening. Overall shortening was greater ow-strength grouts. For similar conditions of grout strength and einforcement, joint shortening in specimens with unfilled slab as at least 33% higher than those with cores filled. Transverse einforcement reduced measured wall shortening. This was probabl o decreased splitting in reinforced wall panels.

TABLE 4 - TEST RESULTS - INTERIOR JOINTS

Specimen Number	Ultimate Load P_u (kips)	Average Wall Stress** (psi)	Wall Panel Concrete Strength (psi)	Grout Strength (psi)	Slab Cores Filled or Unfilled	Observations at Ultimate Load	Remarks
JM-1	350	1820	4860	3000	Filled	Wall Splitting+	Poor Dry Packing (inadequately packed)
J-1	300	1560	4860	3000	Filled	Wall Splitting+	
B-6	343	1790	5380	2730	Unfilled	Grout Crushing	--
B-7*	360	1870	5380	3240	Unfilled	Grout Crushing	--
B-5	440	2290	5420	2980	Filled	Grout Crushing & Wall Splitting	Both Upper & Lower Walls Split
B-2*	460	2400	5310	3260	Filled	Grout Crushing	--
B-3A*	440	2290	4810	4510	Unfilled	Grout Crushing	--
J-2	465	2420	4820	5000	Filled	Wall Splitting+	--
J-3*	520	2710	4820	5000	Filled	Grout Crushing	--
B-4*	525	2730	5310	6800	Filled	Lower Wall Splitting	Upper Wall & Grout Uncracked
B-1*	266	1380	4810	4510	Filled	Slab Crushing	No Grout Column, Slab Cores Filled

*Wall Panels reinforced [illegible]

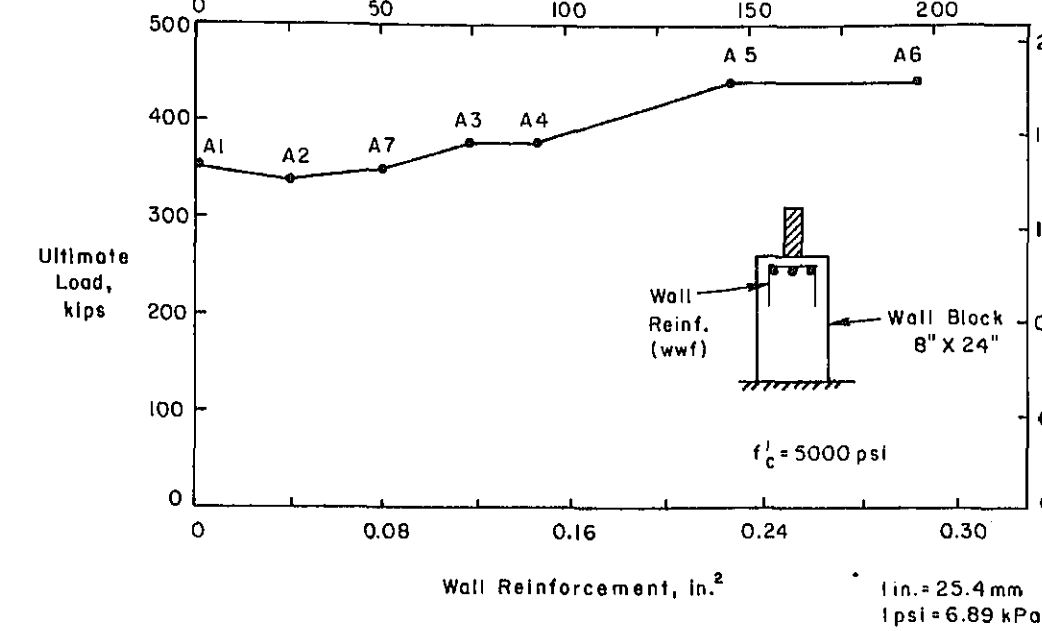


Fig. 9 Splitting Tests - Series A

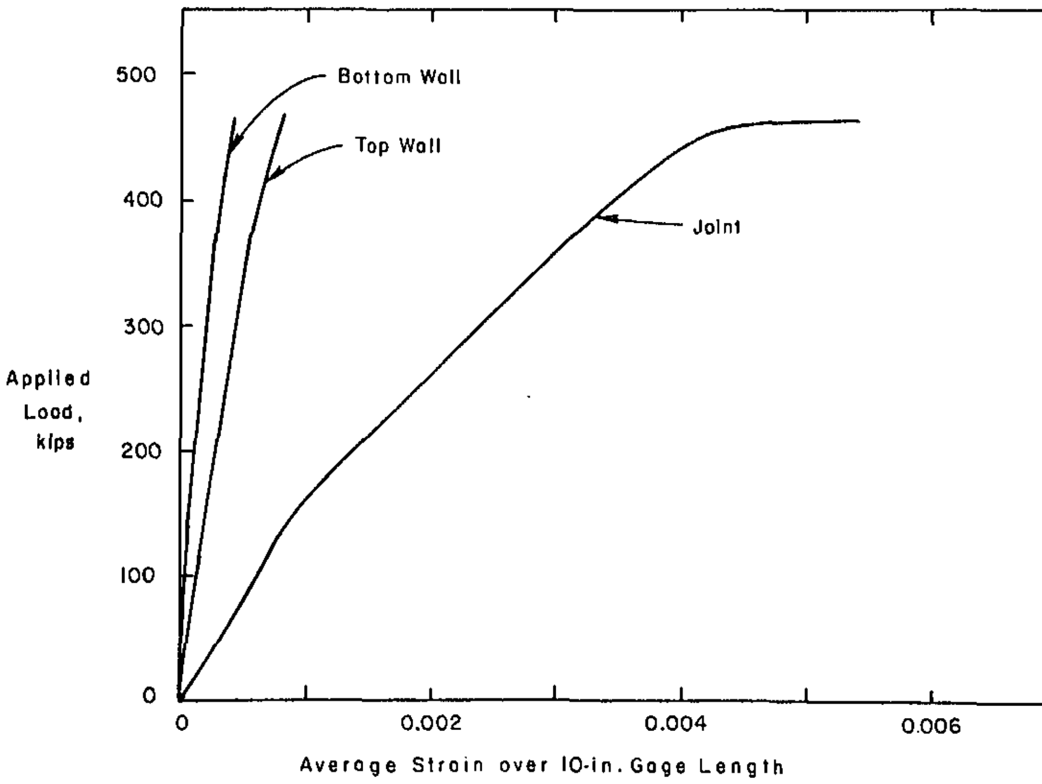


Fig. 10 Load versus Shortening for Specimen J-2

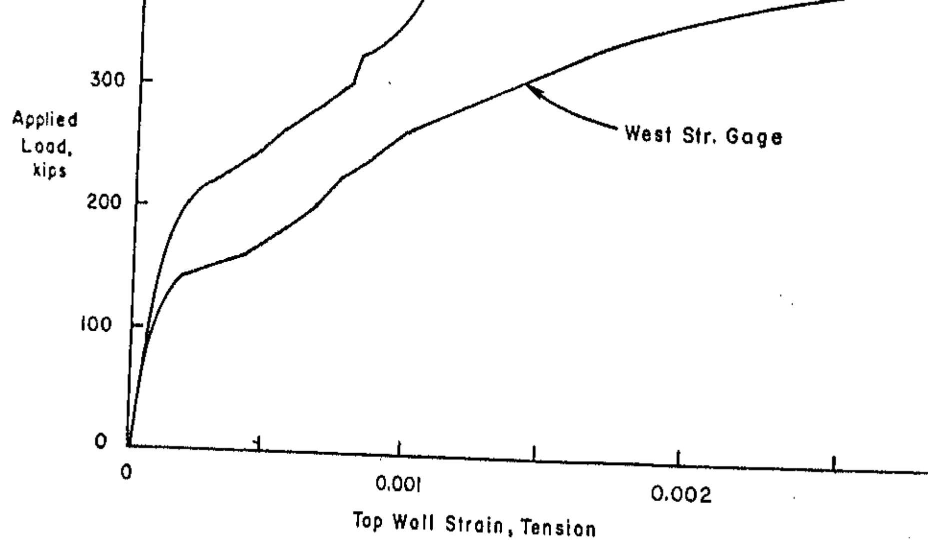


Fig. 11 Load versus Top Wall Strain for Specimen J-2

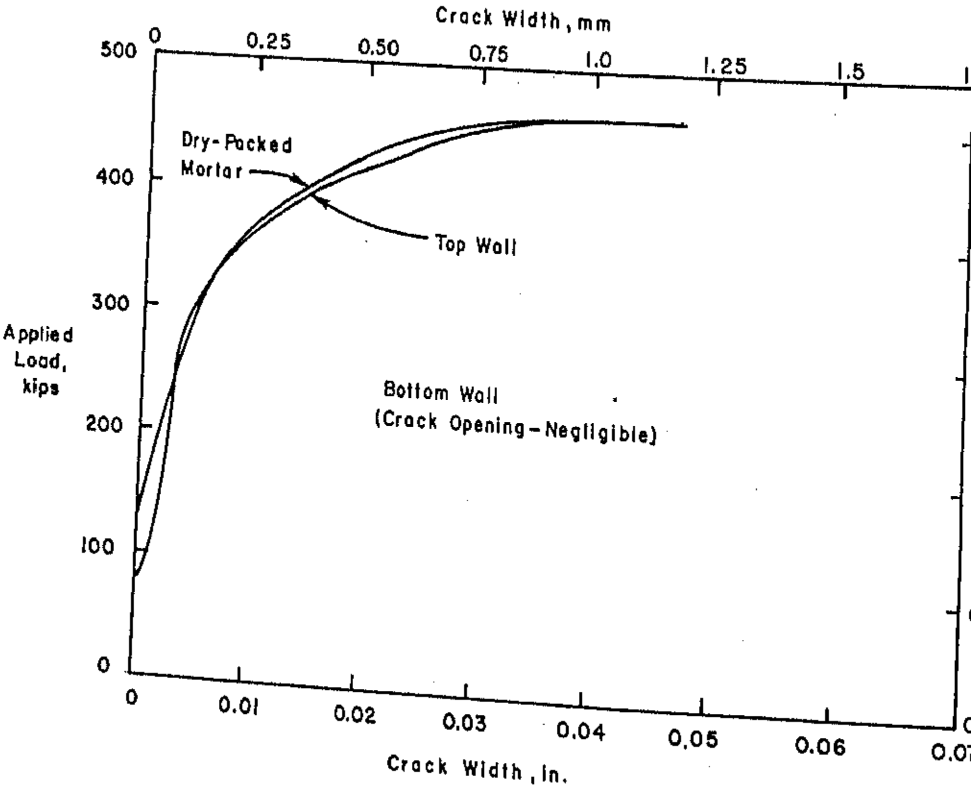


Fig. 12 Load versus Wall Separation for Specimen J-2

Vertical load can pass through an interior joint from the upp
the lower wall in either of two distinct fashions.

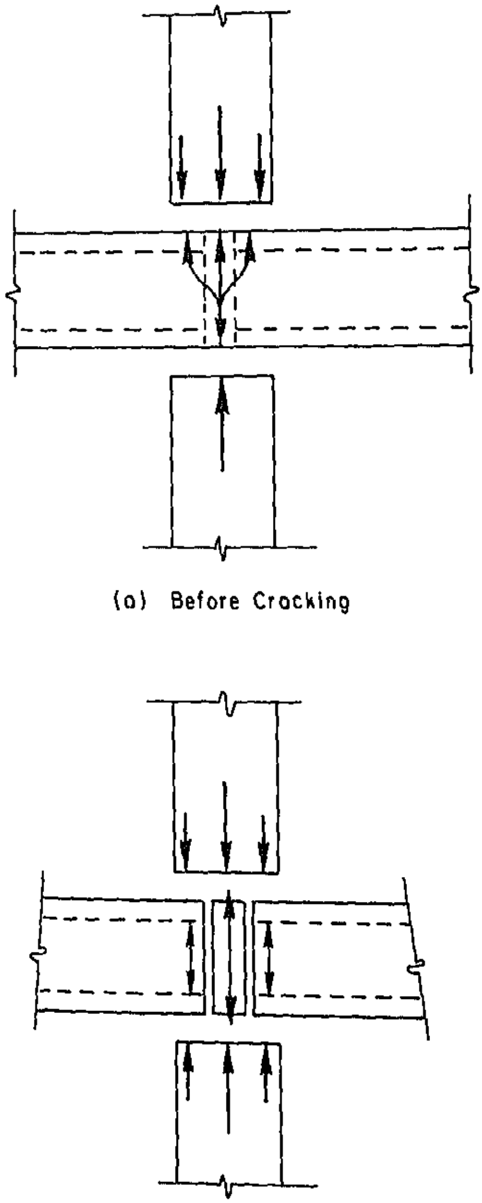
In the first case shown schematically in Fig. 13(a), the join
in a monolithic fashion. Stresses across the top of the joi
the most part uniform. However, due to soft bearing pads b
slabs, the load is funnelled into the bottom of the grout col
a stress concentration in the lower portion of the joint as sh
stresses are transferred at the slab-grout column interface.

In the second case, shown schematically in Fig. 13(b), the joi
of three distinct vertical "columns": a grout column in the c
a column on either side. The outer columns consist of the
slabs and bearing pads. The amount of load that each "colum
varies with the stiffness of that column in relation to
joint. Uniform material properties produce generally unifor
across the joint, while greatly differring properties ca
concentrations.

For a particular interior joint, load flow patterns and be
governed by four variables:

1. Compressive strength of the grout as related to th
sive strength of the wall and slab concrete is one
For purposes of discussion, "low", "medium",
strength grouts are defined as having compressive
respectively, less than, equal to and greater
strength of the slab and wall concrete. The sla
concrete are assumed to have equal strength.

2. Extension of the grout into the hollow cores of th
another variable. Hollow cores are considered fil
grout extends at least to the plane of the face of t



(a) Before Cracking

(b) After Cracking

Fig. 13 General Behavior - Interior Joints

third variable. The reinforcement consists of nomi
verse welded wire fabric as shown in Fig. 3.

4. Stress level in the joint is a fourth variable.

The effects of these variables are discussed in the following s

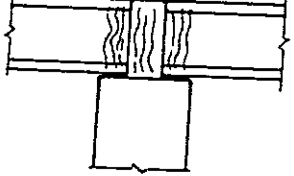
3.3.1 <u>Case 1: Low Strength Grout, Cores Unfilled, Walls</u>
<u>or Unreinforced</u>

For Case 1 shown in Fig. 14(a) load flow is through discr
cal columns. Since the slab cores are unfilled and the s
selves are supported on soft bearing pads, the grout
independent of the slab and carries most of the load.
strength less than the wall strength, increasing loa
grout column crushing, identified as Stage 1. With the l
grout column, load is transferred to the two slab ends
their lower net area these eventually crush before da
wall. This is identified as Stage 2. Since the capac
grout column is generally greater than that of the com
ends, maximum capacity is reached at Stage 1.

Stresses in the wall panels never control. Conseque
behavior and capacity of this joint configuration are no
by reinforcing. This behavior was observed in Specimen
B-7. Specimen B-6 after testing is shown in Fig. 15(a).

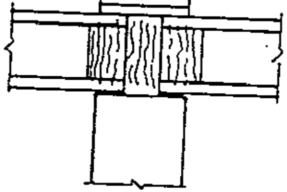
3.3.2 <u>Case 2: Low Strength Grout, Cores Filled, Walls Re</u>
<u>or Unreinforced</u>

For Case 2 with filled cores as shown in Fig. 14(b),
behaves initially as a monolithic element. The funnell
is accomplished through shear between the grout colum
grout cores. Vertical stress is initially uniform at



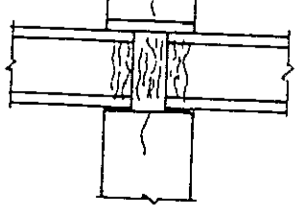
(a) Low strength Grout, Cores Unfilled, Walls Reinforced or Unreinforced

Load Stage
*1 - Grout Crushes
2 - Slab Ends Crush



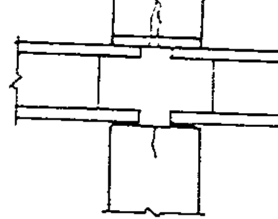
(b) Low Strength Grout, Cores Filled, Walls Reinforced or Unreinforced

1 - Grout Cores Shear Off
*2 - Grout Crushes
3 - Slab Ends Crush



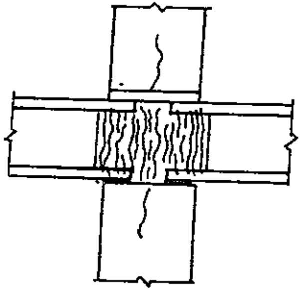
(c) Medium Strength Grout, Cores Unfilled, Walls Reinforced or Unreinforced

1 - Both Walls Crack
*2 - Grout Crushes
3 - Slab Ends Crush



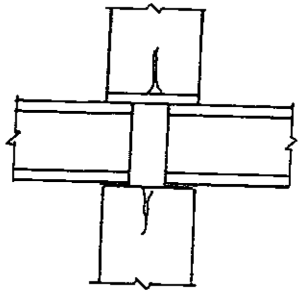
(d) Medium Streng
Grout, Cores
Walls Unreinf

1 - Grout Cores
2 - Both Walls C
*3 - Upper Wall S



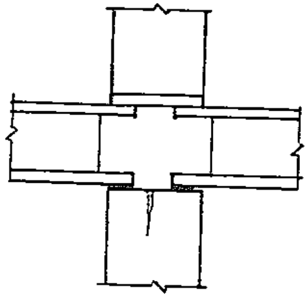
(e) Medium Strength Grout, Cores Filled, Walls Reinforced

Load
1 - Grout Cores Shear Off
2 - Both Walls Crack



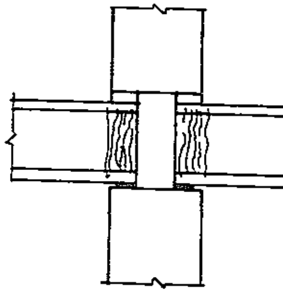
(f) High Strength Grout, Cores Unfilled, Walls Reinforced or Unreinforced

1 - Both Walls Crack



(g) High Strength Grout, Cores Filled, Walls Reinforced or Unreinforced

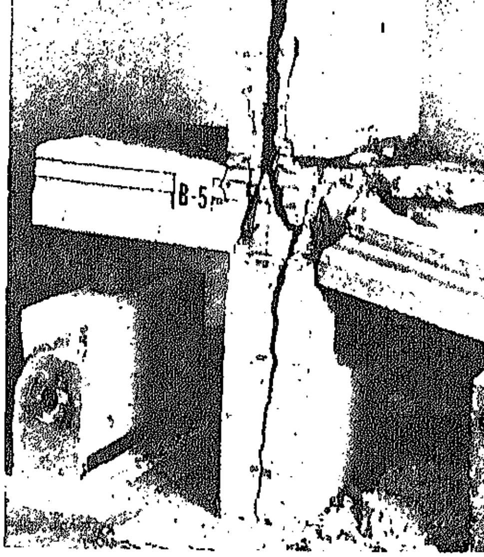
1 - Lower Wall Cracks



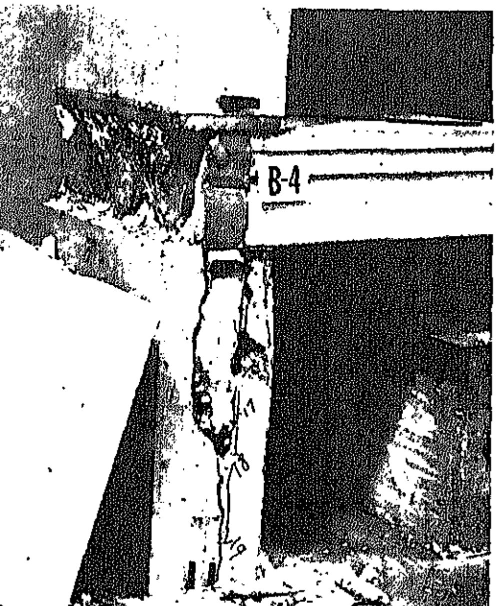
(h) No Grout in
Walls Reinfor
Unreinforced

1 - Slab Ends C

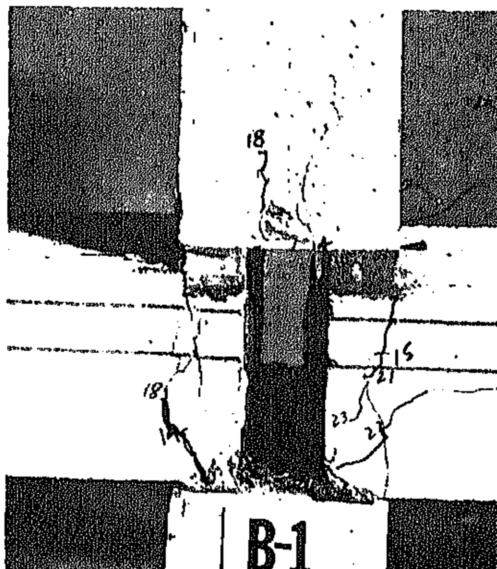
(a) Grout Crushing



(b) Upper Wall Splitting



(c) Lower Wall Splitting



(d) Slab Crushing

Fig. 15 Damage Patterns at Ultimate Load - Interior Jc

grout cores is reached and the grout cores are shear
grout column. This is identified as Stage 1.

Following Load Stage 1, the load flow is through di
columns. Due to the soft bearing pads under the
grout column carries most of the load. With grou
than wall strength, increased load produces g
identified as Stage 2, and load is transferred to
Although the slab ends have additional strength du
cores, they are still weaker than the wall element
the slab ends is the final stage. This type o
evident in Specimens B-2 and B-5. Secondary splitt
also occurred in Specimen B-5, shown in Fig. 15(b).
the maximum joint capacity is reached when grout
Stage 2. Stresses in the wall panels never b
consequently reinforcing does not affect behavior
this joint configuration.

3.3.3 Case 3: Medium Strength Grout, Cores Unfille Reinforced or Unreinforced

For Case 3 shown in Fig. 14(c), load flow is throu
tical columns. The soft bearing pads and unfille
slab ends cause the grout column to support most of
leads to vertical stress concentrations at the wal
duces horizontal tensile stresses in the walls.
cracks the upper and lower walls, identified as St
increase in load, however, causes grout crushing be
splits. This is identified as Stage 2. Grout crus
by load transfer to the slab ends and eventual sl
identified as Stage 3. The capacity of the grout c
than that of the combined slab ends. As a result,
reached at Load Stage 2.

nominal cracks but not high enough to warrant reinforc
behavior and capacity of the joint are not expected to b
by reinforcing. Specimen B-3A containing reinforcement
this behavior.

3.3.4 Case 4: Medium Strength Grout, Cores Filled, Walls Unreinforced

For Case 4 shown in Fig. 14(d), grouted cores cause the
respond initially as a monolithic element. Vertical s
uniform at the top of the joint and concentrated in
column at the bottom of the joint. As load is increas
capacity of the medium strength grout cores is reached
grout cores are sheared off from the grout column.
identified as Stage 1.

Following Stage 1, load flow is through discrete vertical
The grout column carries most of the load, but not as mu
Case 3. This is due to the increased stiffness of the gro
end cores versus the ungrouted cores in Case 3. The vertic
concentrations at the wall ends caused by the grout colu
tensile stresses in the walls. Increased load causes
both the upper and lower walls. This is identified as Stag

For the same total vertical wall load, the grout column in
has slightly lower stress than in Case 3. The difference
to split the unreinforced walls, identified as Stage 3.
havior was observed in Specimen J-2, where the upper wall s

3.3.5 Case 5: Medium Strength Grout, Cores Filled, Walls Reinforced

This joint configuration, shown in Fig. 14(e), is identica
of Case 4 with the exception of the addition of transverse
reinforcing in both upper and lower wall panels. Behavio
identical to that of Case 4 through Load Stage 2. As th

grout crushing, identified as Stage 3. Load is then t
into the slab ends which also eventually crush. This is
as Stage 4. The capacity of the grout column confined be
slab ends, is generally higher than that of the combine
slab ends. Therefore, ultimate capacity is reached when
crushed at Stage 3. This behavior was observed in Specime

3.3.6 Case 6: High Strength Grout, Cores Unfilled, Walls Reinforced or Unreinforced

For Case 6 shown in Fig. 14(f), no specimen was tested. based on observations from the other tests, the behavi anticipated. Load flow is through discrete vertical colu soft bearing pads and unfilled cores of the slab ends grout column to support most of the load. The grout col higher strength than the wall. Consequently, horizonta stresses in the walls, due to the vertical stress conce would become critical long before the grout column ca reached. Increased load first cracks the upper and lov and then splits them. This is identified as Stages 1 a spectively. Splitting will occur whether or not the nominally reinforced.

3.3.7 Case 7: High Strength Grout, Cores Filled, Walls R or Unreinforced

For Case 7 shown in Fig. 14(g), The grouted cores cause to respond as a monolithic element. Vertical stress is the top of the joint and concentrated in the grout colu bottom of the joint. Under increasing load, the grout co shear off the grout column because of the increased shea of the high strength grout. Instead, the vertical stre tration at the bottom of the joint causes horizontal tens buildup in the lower wall. These latter stresses becom

in load first cracks the lower wall and then splits it.
identified as Stages 1 and 2, respectively. Splitting w
whether or not the walls are nominally reinforced. This
was observed in Specimen B-4, shown in Fig. 15(c).

3.3.8 Case 8: No Grout in the Joint, Walls Reinforced or Unreinforced

Case 8, shown in Fig. 14(h), represents an extreme limit
Load flow is solely through the outside slab ends. Capaci
joint is reached as the slab ends crush, identified as
Stresses in the wall panel never become critical, conseque
behavior and capacity of the joint are not altered by re
This behavior was observed in Specimen B-1, shown in Fig.

3.4 Effect of Variables on Joint Strength

The effects of variables on interior joint strength may be sum
follows:

1. A change in a variable to cause a more uniform
compressive stress across the width of the joint
increases the vertical load-bearing capacity of the j

2. Under certain circumstances, control of vertical cr
walls increases the vertical load carrying capacit
joint.

Based on the variables examined, a list of interior joint conf
is given in Table 5. The purpose of the table is to list the
figurations in ascending order of capacity. Behavior of joint
tions that were not tested have been estimated.

TABLE 5 - INTERIOR JOINT CONFIGURATION IN ASCENDING ORDER OF CAPACITY

Specimen	Joint Configuration	Strength of Grout	Cores Filled	Walls Reinforced	Behavioral Case	Behavior at Ultimate
B-1	JC1	No Grout	No	Either	8	Slab End Crushing
B-6, B-7	JC2	Low	No	Either	1	Grout Crushing
B-2, B-5	JC3	Low	Yes	Either	2	Grout Crushing
B-3a	JC4	Medium	No	Either	3	Grout Crushing
-	JC5*	High	No	No	6	Wall Splitting
J-2	JC6	Medium	Yes	No	4	Wall Splitting
-	JC7*	High	No	Yes	6	Wall Splitting
-	JC8*	High	Yes	No	7	Wall Splitting
J-3	JC9	Medium	Yes	Yes	5	Grout Crushing
B-4	JC10	High	Yes	Yes	7	Wall Splitting

*Rank estimated based on test results for other specimens.

Grout strength ranging from about 2700 psi to 6800 psi (18
46.9 MPa) had a significant effect on joint strength.
ultimate loads versus grout strengths for test specimens
in Fig. 16. It can be seen that joint strength generally
with grout strength, provided the capacity was controlled
crushing. However, as indicated in Table 5, for joint c
tion JC10, high strength grout alone did not ensure grea
capacity. As shown in Fig. 16 for Specimen B-4, joint str
controlled by wall splitting, and grout strength was never

3.4.2 Transverse Wall Reinforcement

Split resisting reinforcement had no effect on strength
configurations JC1 through JC4. In these configuration
strengths were controlled by grout crushing. This is show
first four joint configurations of Table 5. Reinforcement
the capacity when the strength was controlled by wall spl
an unreinforced wall. This corresponds to joint configura
and JC9 and was observed in Specimens J-2 and J-3.

3.4.3 Filled Slab Cores

For similar conditions of grout strength and wall reinf
the filled cores in the connection region increased joint
Filled cores increased the stiffness of the slab ends the
tributing to a more uniform vertical stress distributio
joint. Consequently, crushing of the grout occurred a
loads.

3.4.4 Applied Floor Moment and Rotation

Several loading conditions were used to determine the inf
moment and rotation on joint strength. The intensity o
trated floor load was such that the negative moment intr

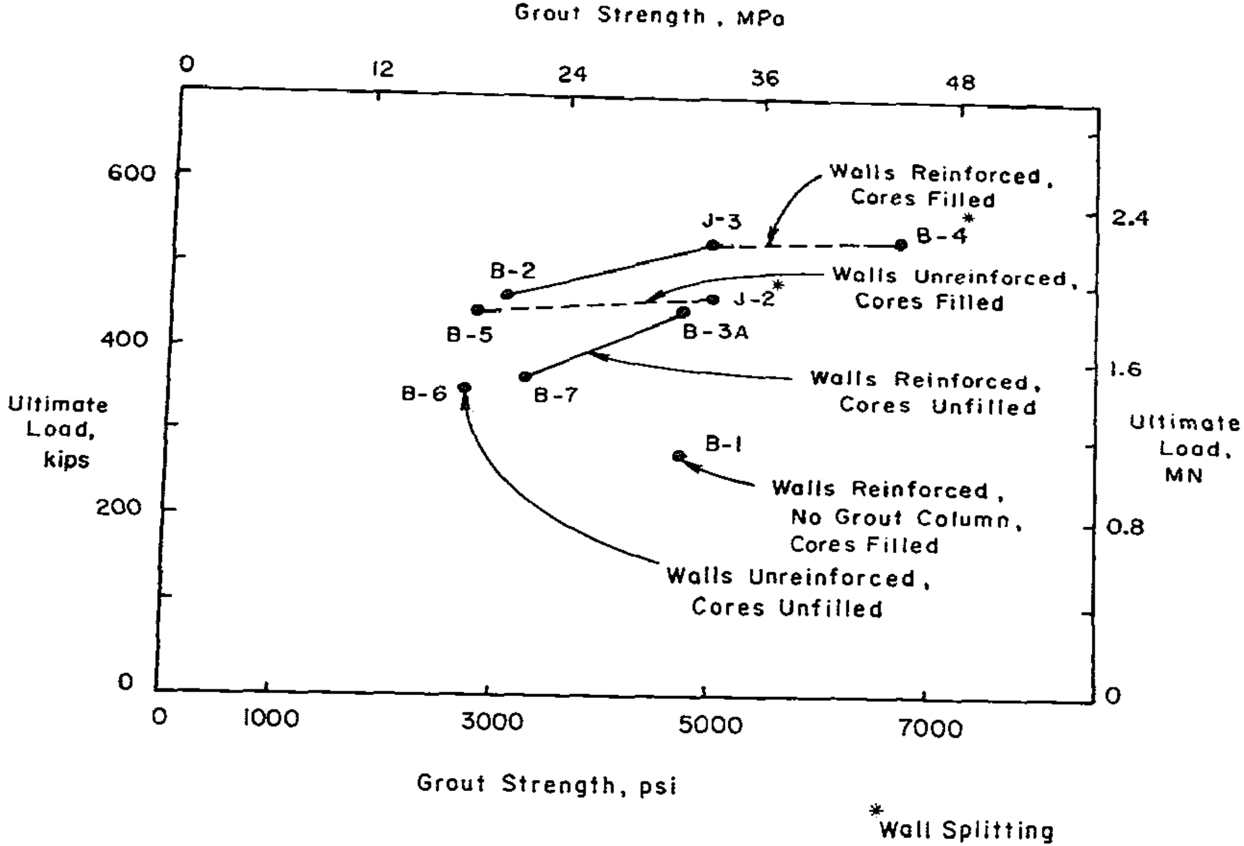


Fig. 16 Interior Joint Strengths, All Series

ratio of about 5 at the joint. The results indicate t
moment and rotation do not affect joint strength sign
Rotation does induce some tensile splitting forces into
wall. However, the effect is minimal and generally
neglected.

3.4.5 Dry Packing

In addition to the variables discussed above, joint perfo
influenced significantly by the uniformity of dry-pack
below the upper wall panel. Well-packed mortar lead t
stresses below the upper wall. Poor dry packing lead to
stresses, thereby substantially reducing joint strengt
premature splitting of the upper wall.

3.5 Experimental Determination of "Stiffness Factor"

Vertical compressive load applied to the upper wall panel is t
to the lower wall panel through the grout column between the f
and the slabs supported on the bearing pads. A greater part o
transfer, however, takes place through the grout column. The
of load transferred through different elements in a horizonta
a function of the relative stiffness of each element in relat
total stiffness of the connection. Stress flow in the slabs
form both across the slab depth and in the direction of the f
Therefore, the effective plank stiffness is indeterminate a
with material properties, load pattern, and geometry of connect
transfer is considered based on measurements made on joint
and grout column shortening.

3.5.1 Joint Shortening

Joint shortening was measured over a height of about
(270 mm). This distance included grout column, dry pack,
3/4 in. (19 mm) each of top and bottom walls.

different elements as shown in Fig. 17(a). This idealiz
closely represents conditions in the joint after vertical
takes place at the end of each floor element separating
column from the grout in the slab cores. Each discrete
considered to act independently.

Using the notation given in Fig. 17(a),

$$\sigma = \frac{\delta\ell_1}{\ell_1} E_1 = \frac{\delta\ell_2}{\ell_2} E_2 = \frac{\delta\ell_3}{\ell_3} E_3 = \frac{\delta\ell_4}{\ell_4} E_4$$

$$\delta\ell_3 = \delta\ell - \delta\ell_1 - \delta\ell_2 - \delta\ell_4$$

$$= \delta\ell - \sigma \left(\frac{\ell_1}{E_1} + \frac{\ell_2}{E_2} + \frac{\ell_4}{E_4} \right)$$

where σ = uniform vertical stress in column,

$\delta\ell_1$, $\delta\ell_2$, $\delta\ell_3$, $\delta\ell_4$ = shortening over heights ℓ_1, ℓ_2, ℓ_3, ℓ
Elements 1, 2, 3, 4, respectively,

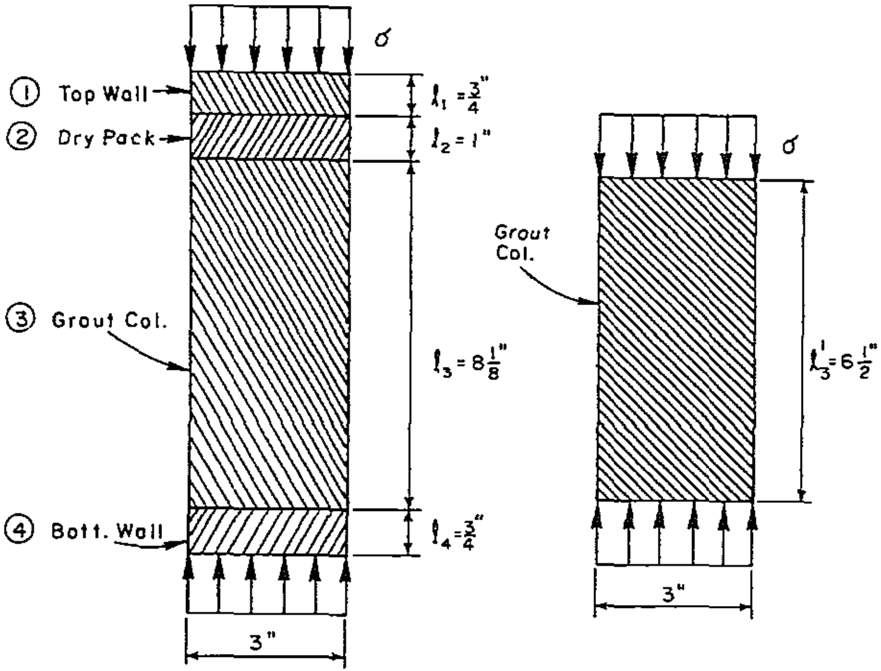
$\delta\ell$ = measured joint shortening = $\delta\ell_1 + \delta\ell_2 + \delta\ell_3 + \delta\ell_4$, and

E_1, E_2, E_3, E_4 = modulus of elasticity of Elements 1,
respectively.

The shortening in grout column, $\delta\ell_3$, was determined from
expression by assuming a uniform vertical stress, σ, and
corresponding values of E_1, E_2 and E_4 from a f
stress-strain curves plotted for materials of different co
strengths. A trial and error method was used to match th
vertical stress with the grout column stress correspondin
culated grout column shortening $\delta\ell_3$.

Therefore, the amount of load transferred through the grou
P_g, is given by:

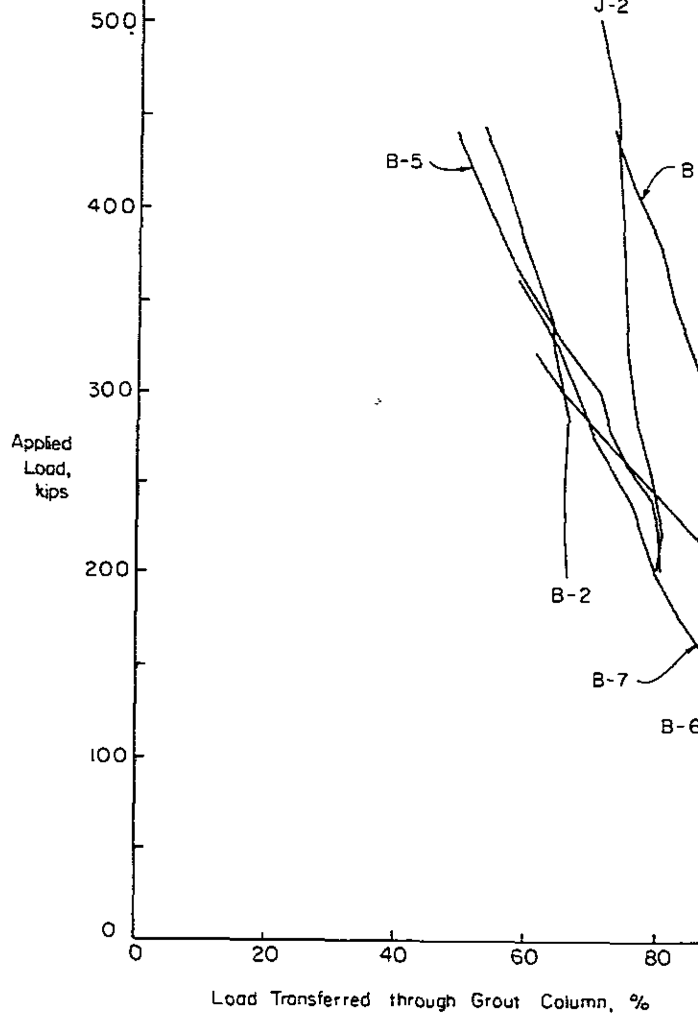
$$P_g = \frac{\delta\ell_3}{\ell_3} (E_3) (A_g)$$



(a) Joint Shortening

(b) Grout Column Shortening

Fig. 17 Idealized Uniform Stress Region



where A_g = cross-sectional area of grout column

3.5.2 Grout Column Shortening

Stress analysis based on total joint shortening described in S tion 3.5.1 was quite complex. It involved materials with diff ent elastic properties. The voids left between different ma rials as a result of construction procedures and subsequ shrinkage were not considered in the analysis. This resulted a high calculated percentage of load transferred through the gr column in the initial load stages.

Shortening in the grout column alone was also measured in Spe mens B-6 and B-7. Strain measurements were taken over a hei of about 6.3 in. (160 mm).

Assuming a uniform stress throughout the length of the gro column as shown in Fig. 17(b), the percentage of applied lo transferred through the grout column was calculated.

$$\sigma = \frac{\delta \ell'_3}{\ell'_3} E_3 \qquad \text{(Eq.}$$

where $\delta \ell'_3$ = shortening over height ℓ'_3 of grout column

Therefore, the amount of load transferred through the grout co is given by:

$$P_g = \frac{\delta \ell'_3}{\ell'_3} (E_3) (A_g) \qquad \text{(Eq. B}$$

Using the procedure described in Sections 3.5.1 and 3.5.2, the p centage of load transferred through the grout column was calcula

ized column by cracking at the slab end and grout co
face. Results for Specimens J-3 and B-4 are not plotted
inconsistent data. Figure 18 shows that the percenta
transferred through the grout column decreased as the
increased.

4.1 Specimen Strength

Ultimate test loads are given in Table 6. For convenience, these results are expressed both as ultimate load, P_u, and as average wall stress. The latter was obtained by dividing the ultimate load by the bearing area of the wall panel. Also given in Table 6 are the observations at ultimate load indicating that crushing of the grout occurred in all specimens.

4.2 General Behavior

As in interior joints, vertical load can pass through an exterior joint in either of two fashions. In the case shown schematically in Fig. 19(a), the joint functions in a monolithic manner. Load is distributed across the top, nonuniformly due to the built-in eccentricity of the joint. At the bottom of the joint, load is funnelled into the grout column due to the soft bearing pads beneath the ends of the slabs.

In the case shown in Fig. 19(b), the joint consists of two discrete vertical "columns": a grout column in the center and a column on one side consisting of the end of the slab. The load that each "column" supports varies with the total stiffness of that column and the eccentricities present within the exterior joint. As there exists a significant built-in eccentricity because of the discrete slab end on only one side, uniform material properties will not produce uniform stresses across the joint, as in the case of interior joints.

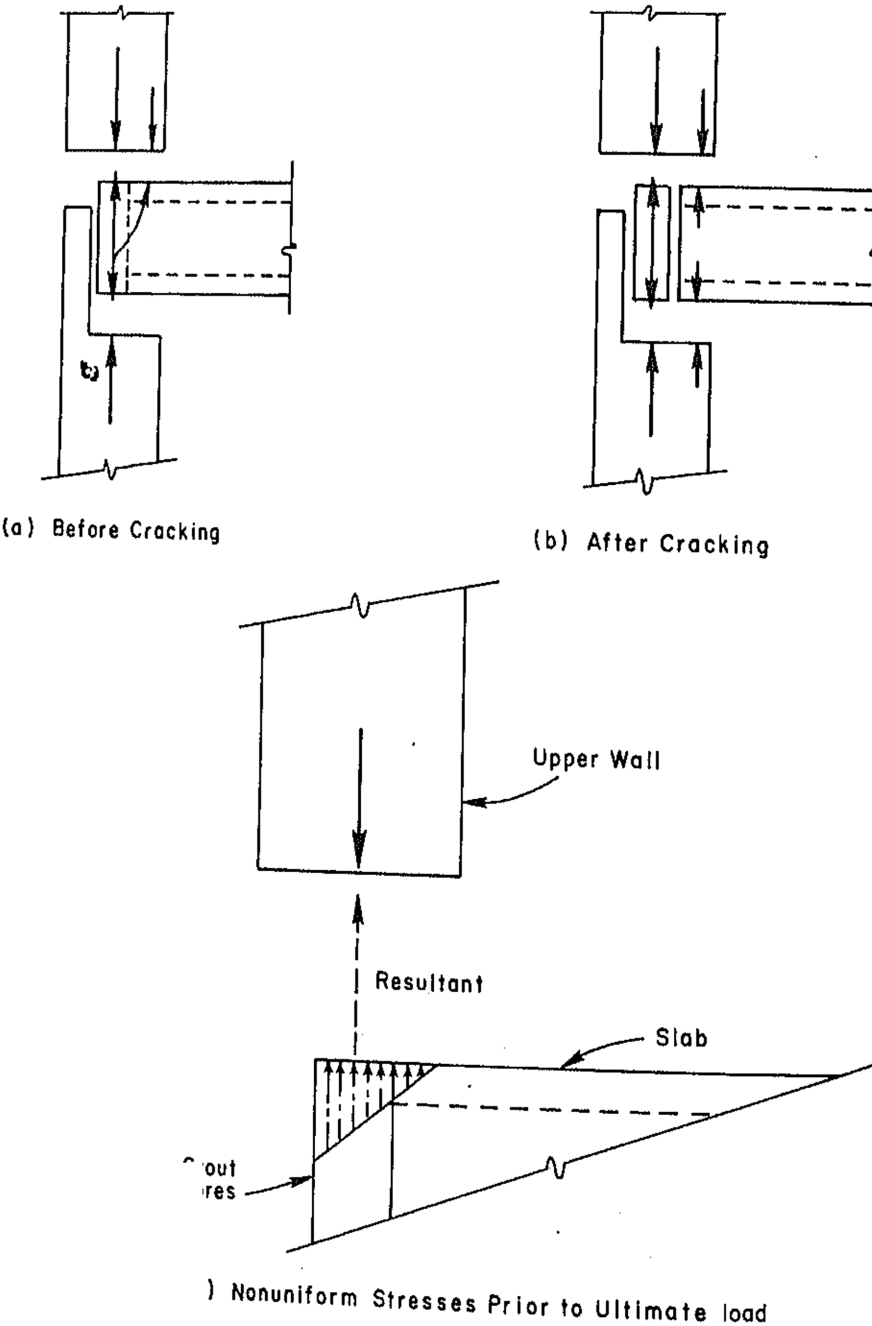
For a particular exterior joint, both load flow patterns and behavior are governed by the same four variables as interior joints described in Section 3.3. However, in exterior joints the effects are much less pronounced. As noted above, the basic configuration of the joint leads to nonuniform stresses no matter what the material properties may be. As shown schematically in Fig. 19(c), the joint initially tends to transfer most of the load to the centrally located grout column. Consequently

TABLE 6 - TEST RESULTS-EXTERIOR JOINTS

Specimen Number	Ultimate Load P_u (kips)	Average Wall Stress** (psi)	Wall Panel Concrete Strength (psi)	Grout Strength (psi)	Slab Cores Filled or Unfilled	Observations at Ultimate Load	Remarks
E-1	300	1560	5420	2980	Filled	Grout Crushing	--
E-2	290	1510	5180	2840	Unfilled	Grout Crushing	--
E-3	280***	1460	5180	4770	Unfilled	Grout Crushing	Poor Dry Packing (inadequately packed)
E-4	380	1980	4900	4630	Filled	Grout Crushing	--
E-5*	400	2080	4900	4510	Filled	Grout Crushing	--

*Wall Panels reinforced with 6x6 - W 2.9 X W 2.9, $A_s = 0.116$ in.^{2}

**Average wall stress obtained by dividing the ultimate load by the bearing area of wall panel (bearing area is 24x8 in.)



General Behavior - Exterior Joints

grout column to the lower wall is substantially higher i
joints when compared to similar interior joints.

4.2.1 Case 1: Low and Medium Strength Grout, Cores Fille Unfilled, Walls Reinforced or Unreinforced

For Case 1, shown in Fig. 20(a), load flow is through dis tical columns when cores are unfilled, and through a element when cores are filled. In the latter cases, ho grout carries most of the load. As load is increased, th crushed before tensile splitting stresses, caused by th stress concentration, become critical in the wall panel. identified as Stage 1.

With the loss of the grout column, load is transferred t ends, which also crush, identified as Stage 2. Since th of the grout column is greater than that of the slab en load is reached at Stage 1.

Stresses in the wall panel never become critical. Ther behavior and capacity of this joint configuration are n by reinforcing. A specimen exhibiting this behavior is Fig. 21. Similar behavior was observed in all specimens mate load.

4.2.2 Case 2: High Strength Grout, Cores Filled or Unfil Walls Reinforced or Unreinforced

No specimens representing Case 2, shown in Fig. 20(b), we The load flow is similar to that of Case 1. Due to the bearing of the wall and to the soft bearing pads beneat ends, the grout again transfers most of the load. The g higher strength than the wall concrete. Consequentl expected that horizontal tensile stresses in the walls, vertical stress concentration, would become critical l the grout column capacity is reached.

(a) Low & Medium Strength Grout Cores Filled or Unfilled, Walls Reinforced or Unreinforced

(b) High Strength Grout, C Filled or Unfilled, Wa Reinforced or Unreinfo

ad
age

*1 - Grout Crushes
2 - Slab Ends Crush

1 - Both Walls Crack
*2 - Both Walls Split

*Ultimate Capacity

Fig. 20 Behavior at Successive Load Stages - Exterior Joints

Fig. 21 Damage Pattern at Ultimate Load - Exterior Joints

tively. Splitting would likely occur whether or not the w
nominally reinforced.

4.3 Effects of Variables on Joint Strength

Grout strength was the only variable in the test program that
strength of the joint. This occurred because the basic configu
the joint caused most of the load to be transferred through
column.

Based on the variables examined, a list of exterior joint c
given in Table 7. The table lists joint configurations in
order of capacity. Behavior of the last two joint configurat
and JC14 have been estimated.

4.3.1 Strength of Grout

Grout strength ranging from approximately 2800 psi to
(19.3 MPa to 33.1 MPa) had a significant effect on joint
Measured ultimate loads versus grout strength are shown i
It can be seen that with the exception of Specimen E-3,
poorly dry packed, joint strength increased with grout str

As suggested in Table 7 for configuration JC13 and JC14,
city of joints with high strength grout is expected to be
by wall splitting.

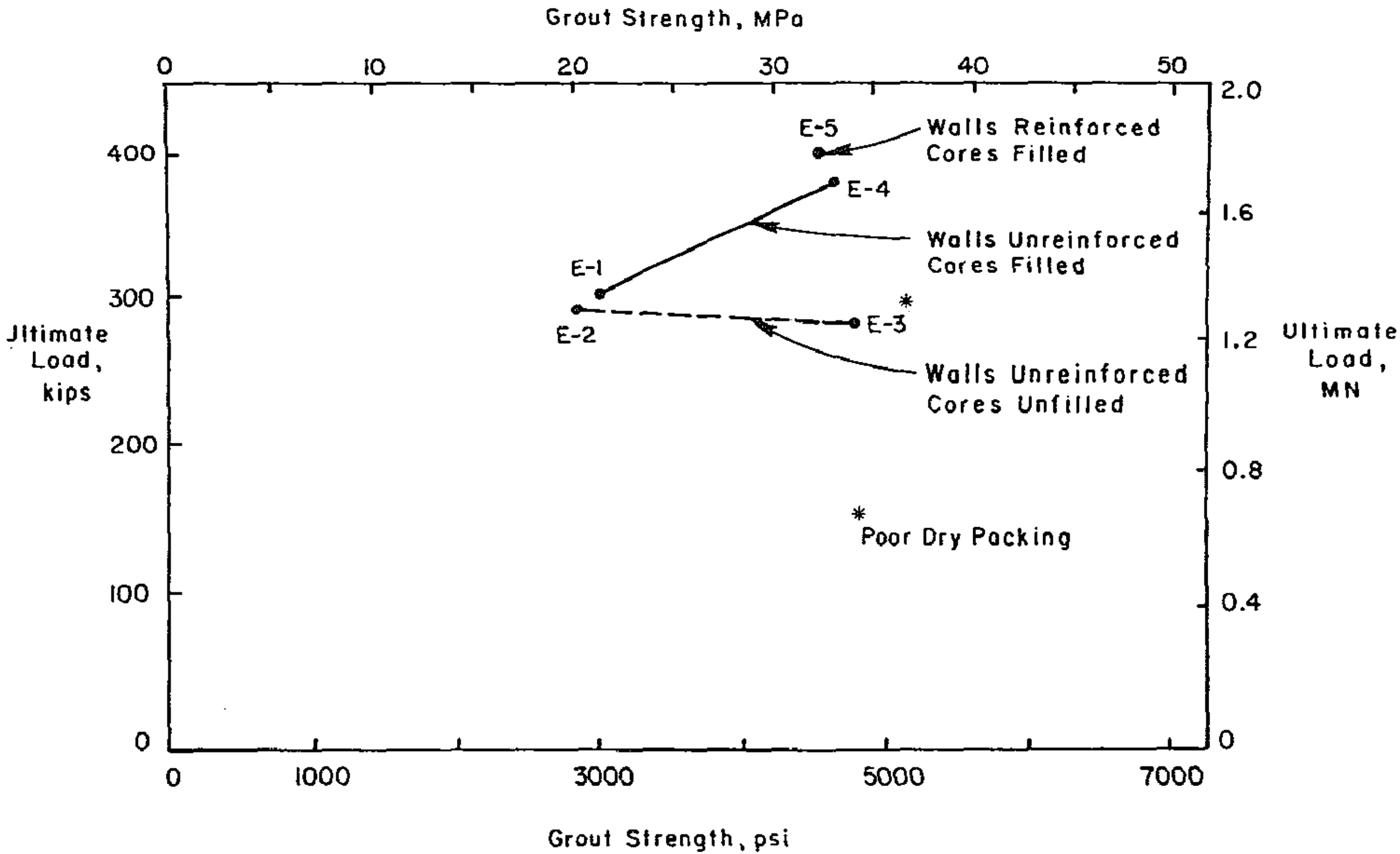
4.3.2 Transverse Wall Reinforcement

Addition of split-resisting reinforcement has no effect
with low or medium strength grout. Reinforcement will
joint capacity only when the mode of behavior at ultimat
splitting in a non-reinforced wall. Joint configurations
JC14 would be expected to perform this way.

TABLE 7 - EXTERIOR JOINT CONFIGURATION IN ASCENDING ORDER OF CAPACITY

Specimen	Joint Configuration	Strength of Grout	Cores Filled	Walls Reinforced	Behavioral Case	Behavior at Ultimate
E-1, E-2	JC11	Low	Either	Either	1	Grout Crushing
E-3, E-4, E-5	JC12	Medium	Either	Either	1	Grout Crushing
--	JC13*	High	Either	No	2	Wall Splitting
--	JC14*	High	Either	Yes	2	Wall Splitting

*Rank estimated based on test results for other specimens.


Grout Strength, MPa
0
10
20
30
40
50
2.0
1.6
1.2
0.8
0.4
0
Ultimate
Load,
MN
400
300
200
100
0
Jltimate
Load,
kips
E-5
Walls Reinforced
Cores Filled
E-4
Walls Unreinforced
Cores Filled
E-1
E-2
E-3
Walls Unreinforced
Cores Unfilled
Poor Dry Packing
0
1000
3000
5000
7000
Grout Strength, psi

Filling the cores in the connection region increases the j
capacity. As the exterior joints have a slab on one side of
joint only, lesser load is transferred through the slab en
compared to the interior joints. Therefore, filling the core
exterior joints will have somewhat less of an effect.

4.3.4 Dry Packing

Poor dry packing can lead to premature joint failure. Dry pac
is more difficult in exterior joints, because mortar has t
packed from one side of the joint only. Consequently, the p
ability of inadequate packing is higher.

1 Prestressed Concrete Institute Methods

recent years, several methods to determine the load capacity of ho
ntal connections in large panel structures have been proposed. T
ction discusses three design procedures proposed by the Prestres
ncrete Institute (PCI)[5].

estressed Concrete Institute Method 1[5] is based on strengths
int components. Applied design load on the joint is distributed
e components of the joint according to the stress-deformation
rength characteristics of the components. It also allows a "confi
nt factor" on the cylinder strength of concrete or grout in the joi

is method is empirical in nature, and is complex to use. There
w experimental data to verify the stress-strain relationships used
e analysis. Elastic properties of the bearing pads used in the expe
ntal tests described in this report differed substantially from
lues suggested in PCI Method 1.

estressed Concrete Institute Method 2[5] is based on elas
alysis of a joint. With this approach, the joint is divided int
ries of discrete vertical "columns." The amount of load that e
olumn" supports is a function of the stiffness of that partic
lumn. The method permits determination of the stress distribution
mponents of the joint under service load conditions. However, Me
has the following limitations:

1. It underestimates the effective stiffness of a slab by li
ing the width of the "slab column" to the bearing length
the floor slab in calculating areas of discrete vert
"columns." However, analytical investigations[2] indic
that additional plank length beyond the edge of a wall p
participates in transferring vertical load from the upper

2. It does not consider the use of hollow-core slabs and th tional stiffness provided by the grout in the slab cores the connection region.

3. It permits determination of stresses in the elastic ran not the load capacity of a joint. Also, the method d consider the effect of wall reinforcement or the poss of a splitting failure when high strength grout is used.

Prestressed Concrete Institute Method 3(5), is based mainly on conducted by the Danish Structural Research Center. Their emp expression seems valid, but is applicable only if grout strengths the joint and the wall concrete strength are similar.

5.2 Proposed Design Procedures

5.2.1 Interior Joints

Vertical compressive load applied to the upper wall is trans to the lower wall through the grout column and the floor ends. A greater part of the load is carried by the grout and slabs carry the rest. Ultimate load, P_u, can be sep into two parts as follows:

$$P_u = P_g + P_s$$

where

P_u = joint strength

P_g = amount of load transferred through the gro column

P_s = amount of load transferred through the flo slabs

The amount of load transferred through slabs can be increase cores are filled. It should be noted, however, that, P_s, not represent the load capacity of an ungrouted connection. I

capacity. Joint capacity is reached when grout in the joint
crushed. Strength of an ungrouted connection will, usually,
much higher than P_s. This strength can be determined direc
from the bearing area of slab ends and the compressive strength
floor slab concrete.

The proposed method limits the maximum useable grout streng
f_u, and thus, ensures that joint capacity is controlled by gr
crushing rather than wall splitting. The maximum useable gr
strength, and consequently joint capacity can, however, be
creased by selecting proper joint variables, such as grout and w
strengths, wall reinforcement, and by filling the slab cor
Therefore, high strength grout can only be used effectively if
walls use high strength concrete, they are reinforced against spl
ting, and the slab cores are filled with grout.

Based on the maximum useable grout strength, f_u, the follow
expression for capacity of interior horizontal joints was develop

$$P_g = K P_u$$

$$P_s = (1 - K)P_u$$

From basic principles,

$$P_g = t L f_u$$

where t = width of the grout column - in this case 3
(76 mm),

L = horizontal length of grout column,

f_u = maximum useable strength of grout defined
follows: compressive strength of grout,
or wall concrete, f'_c, whichever is less,
not more than 4000 psi (27.6 MPa), unless
walls are reinforced against splitting and s
cores are filled with grout,

K   factor representing the percentage
       load transferred through the grout
       was found to increase linearly fro
       value of 0.65 for a grout strength
       (17.24 MPa) to a value depending
       of grout in the joint, f_g.

For simplicity, K can be taken as follows:

$$K = 0.65 + \left[\frac{f_g - 2500}{50,000}\right] \text{ for } f_g \text{ in psi,}$$

$$= 0.65 + \left[\frac{f_g/0.0069 - 2500}{50,000}\right] \text{ for } f_g$$

Therefore, $P_u = P_g/K$

The filled core factor, C, can be used to account for strength due to increased slab stiffness. The filled is inversely proportional to the square root of grout strength, f_g.

Therefore, $P_u = \frac{t\,L}{K} f_u\, C$

where C = filled core factor determined as follows

For filled slab cores:

$$C = 1.4\sqrt{\frac{2500}{f_g}} \text{ for } f_g \text{ in psi, or}$$

$$= 1.4\sqrt{\frac{2500}{f_g/0.0069}} \text{ for } f_g \text{ in MPa,}$$

but not less than 1.0

For unfilled slabs cores:

$$C = 1.0$$

applicable to other types of joints with different geo material properties. However, the configuration used in thi tigation is representative of horizontal joints used in lar structures.

5.2.2 Exterior Joints

It appears from the tests that for exterior joints, mos load applied to the upper wall panel is transferred to t wall panel through the grout column. Stiffness provided slab may, therefore, be ignored.

Therefore, $P_u = P_g$

Based on the experimental study on exterior joints, the expression is proposed for determining a conservative value joint strength:

$$P_u = t\,L\,f_u\,C$$

where P_u = joint strength,

t = width of grout column - in this case 3 (76 mm),

L = horizontal length of grout column,

f_u = maximum useable strength of grout de follows: compressive strength of grou wall concrete, f'_c, whichever is less, more than 4000 psi (27.6 MPa), unl cores are filled with grout,

f_g = compressive strength of grout in the j

C = filled core factor determined as follo

For filled slab cores:

$$C = 1.2\sqrt{\frac{2500}{f_g}} \quad \text{for } f_g \text{ in psi, or}$$

but not less than 1.0

For unfilled slab cores:

$$C = 1.0$$

It should be noted that the above expression is based on number of tests applied to one type of joint configuration. not be applicable to other types of joints with different geo cal or material properties. However, the configuration us this investigation is representative of horizontal joints co used in large panel structures.

5.3 Comparison of Measured and Calculated Strengths

Strengths for the interior joint specimens were calculated fro three PCI Methods and from the proposed design expression. These compared with the measured strengths. The values are listed in Tab

Prestressed Concrete Institute Method 1 is based on stress-deform characteristics of the joint components. An increase in grout stre allowed due to its confined nature in the joint. However, the m does not distinguish between slab cores filled and unfilled. The mum value of confinement factor is arbitrarily fixed at 2.0. In c lating the load capacities using this method, confinement factors o and 1.0 were assumed for slab cores filled and unfilled, respecti Furthermore, there is no provision for additional joint strength du reinforced wall panels, or loss of strength due to wall splitting p to grout crushing in unreinforced wall panels. Consequently, the ca lated strengths of Specimens J-2, J-3 and B-4 were substantially dif ent from measured strengths.

Prestressed Concrete Institute Method 2 gives stress distribution u service load conditions only. In calculating the load capacity of jo

Specimen Number*	Calculated Load Capacity ** (kips)				Measured Strength (kips)
	PCI Methods			Proposed Method	
	1	2	3		
B-6	211	286	252	300	343
B-7	249	332	299	351	360
B-5	460	309	275	417	440
B-2	502	334	301	433	460
B-3A	344	445	417	417	440
J-2	761	488	462	411	465
J-3	761	488	462	496	520
B-4	1028	642	628	519	525

ial Specimens JM-1 and J-1 have been omitted because their failure e to poor dry packing. Specimen B-1 has been excluded because t s no grout column provided.

e Table 2 for strength of grout, concrete and other variables.

tric equivalent: 1 kip = 4.448 kN

from this method, the stress or load distribution at ultimate was ass to be the same as at service load. Also, since this method does not into account the effect of splitting in the walls, calculated stren of Specimens J-2 and B-4 are overestimated. These specimens conta high strength grout. Wall splitting occurred before the grout crus There is no provision for added joint strength due to filled cores. Therefore, calculated strengths of Specimens B-2 and B-5 underestimated.

Prestressed Concrete Institute Method 3 is applicable only when g and wall strengths are approximately equal. For the present tests,

However, strength of Specimen J-3 with reinforced wall panels, was under estimated. Values for grouts with lower and higher strengths are als given in Table 8 for comparison. In these specimens, agreement betwee calculated and measured strengths is poor.

Out of all the methods proposed prior to the present research, P Method 2, based on elastic analysis of a joint provided the mos reasonable approach for designing interior wall-to-floor connection However, as described earlier in this section, this method gives stre distribution in the elastic range only, and it does not consider th cases where joint capacity is limited by wall splitting. Consequentl the use of this method for predicting joint strength is very limited.

The proposed design method described in Section 5.2 is based on the pr sent experimental investigation. It predicts the joint capacity taki into account all modes of joint behavior both under service and inelast loading conditions. As shown in Table 8, the load capacity calculat by the proposed method agrees very favorably with the measured joi strengths.

Capacities for exterior joint specimens were also calculated from t proposed design expression. A comparison with measured values is giv in Table 9.

Specimen Number*	Joint Strength** (kips)	
	Calculated by Proposed Method	Measured
E-1	236	300
E-2	204	290
E-3	288	280*
E-4	333	380
E-5	325	400

*Specimen E-3 has reduced joint capacity due to poor dry packing.

**See Table 3 for strength of grout, concrete and other variables.

Metric equivalent: 1 kip = 4.448 kN

6.1 Interior Joints

1. Joint capacity increases with grout compressive stre joint strength is controlled by grout crushing. Th when the grout strength is less than about 80% o concrete compressive strength.

2. Wall Splitting is not a problem when low-strength used. However, for unreinforced walls, when the pressive strength exceeds about 80% of wall concret sive strength, wall splitting occurs prior to grou its strength. When the walls are adequately development of full grout strength results in incre capacity. The amount of wall reinforcement require splitting increases with grout compressive strength.

3. Filling slab cores with grout directly affects strength. For low-strength grouts, joint strength substantially with filled cores. With medium stren behavior at ultimate load changes from grout crushi splitting when slab cores are filled. With both high strength grouts, wall reinforcement limits spl thus, the benefits from filling the cores are utiliz

4. The quality of dry pack below the upper wall panel nificant effect on the joint strength. Inadequate with voids leads to a substantial loss of joint capa

5. Floor moment and rotation do not have a significant the strength of a wall-to-floor connection.

(Eg. B-7) agree very closely with the measured joint st

6.2 Exterior Joints

1. When grout strength is equal to or less than wall compressive strength, joint capacity increases with gr pressive strength.

2. Filled slab cores in exterior joints minimize the e built-in or accidental eccentricity. Joint strength, is not significantly improved.

3. When grout strength is less than or equal to wall compressive strength, wall splitting does not occur.

4. When the grout strength is greater than the wall stre is anticipated that wall splitting will occur unless t are adequately reinforced.

5. The proposed expression (Eq. B-8) gives conservative v load capacities for exterior horizontal joints when with the measured strengths.

Detailed recommendations for specific analysis techniques anc criteria are given in Report 5[2].

A_g = cross-sectional area of grout column

C = confinement factor

E_1 = modulus of elasticity of upper wall panel

E_2 = modulus of elasticity of dry pack

E_3 = modulus of elasticity of grout in the joint

E_4 = modulus of elasticity of lower wall panel

f'_c = compressive strength of concrete

f_g = compressive strength of grout in the joint

f_u = maximum useable strength of grout for calculating joint st

F.M. = fineness modulus

K = stiffness factor

L = horizontal length of grout column

$\delta\ell_1$ = shortening measured over a height ℓ_1 at the lower end of u
panel (See Fig. 17)

$\delta\ell_2$ = shortening measured in dry pack, total height = ℓ_2 (See Fi

$\delta\ell_3$ = shortening measured in grout column, total height = ℓ_3 (Se

$\delta\ell_4$ = shortening measured over a height ℓ_4 at the upper end of l
panel (See Fig. 17)

$\delta\ell'_3$ = shortening measured in grout column over a height ℓ'_3 (See

$\delta\ell$ = $\delta\ell_1 + \delta\ell_2 + \delta\ell_3 + \delta\ell_4$ = total joint shortening measured ov
$\ell = \ell_1 + \ell_2 + \ell_3 + \ell_4$ (See Fig. 17)

LP = large panel

P_g = vertical load transferred through grout column

P_u = joint strength

t = thickness of grout column

σ = vertical stress in grout column

dental eccentricity:	An eccentricity which exists as a result of errors in either the manufa or erection process.
mbly:	An aggregate of panels.
ing area:	Area of the wall panel through which cal compressive force is applied joint; 24 x 8 in. (610 x 203 mm) i case.
t-in eccentricity:	An eccentricity which exists as a res exterior joint configuration.
ections:	A position or region where two or more ing components, panels or assemblies together or united.
ection stiffness: vertical loads)	The sum of stiffnesses of grout and pl "columns" composing a connection.
inement factor:	A factor used to allow for increased c sive strength of grout, reflecting th fined nature of material in the joint.
inuity:	The capacity for load transfer betwe or more elements where load is axial, moment, or any combination thereof.
ge pattern:	Mode of behavior at ultimate load.
rmation:	A change in dimension or shape.

area, also, the mixture so placed.

Dry-packed mortar: A mortar mixture sufficiently dry solidated by heavy ramming.

Ductility: The measure of a structural c (element or joint) ability to inelastic deformations, i.e. the the maximum deformation to th deformation.

Exterior joints: Horizontal joints connecting exter panels and floors.

Filled slab cores: Hollow cores of precast concrete filled with fluid grout (extendi 3-1/2 in. (89 mm) into the cores).

Floor moment and rotation: Moment applied to simulate actual conditions (less than calculated moment).

Floor panel: Horizontal precast concrete element cally consisting of hollow core concrete planks.

Floor plank: A horizontal precast concret element cally extruded and reinforced with hi strength steel. Also known as holl or hollow-core slab.

Grout: Mixture of cementitious material and gate to which sufficient water is a produce pouring consistency without gation of the constituents.

Grout stiffness ratio:	Ratio of grout column to the to tion stiffness; also defined a factor.
Grout strength:	Average compressive strength of ured on six 6x12-in. (152x305 mm Ranges of strength are: Low: 2500 to 4000 psi (17.2 to Medium: 4000 to 5500 psi (27.6 to High: 5500 to 7000 psi (37.9 to
Horizontal joint:	The zone common to the wall and in a horizontal direction.
Integrity of connection:	The ability of a connection loads from one portion or element while retaining its structural st
Interior joints:	Horizontal joints connecting in panels and floors.
Joint strength:	The maximum load sustained by a j
Large panel (LP) structures:	A structural system composed load-carrying elements of large panels with precast floors an panels or planks.
Optimum wall reinforcement:	Minimum transverse reinforcement the ends of wall panels to kee from splitting before grout is the joint.
Service load:	Unfactored normal loading conditi

Strength of grout:	See grout strength.
Transverse wall reinforcement:	Optimum amount of reinforcement the end of wall panels to limit
Ultimate joint load:	See joint strength.
Ultimate load: (general)	The maximum load which may be connection, member or a structu failure; also, the load at which unit or structure fails.
Wall panel:	A vertical precast concrete e load-bearing or non-load-bear one-story in height, with leng ranging from 10' to 45'.
Wall reinforcement:	See transverse wall reinforcemen

Assembly of Specimens

st specimen consisted of precast top and bottom wall panels, a
ssed concrete hollow-core slabs assembled as shown in Figs. 3 and

ssemble a specimen, the lower wall block was plastered to the flo
hollow-core planks were lowered into position on top of it. The
slabs were supported on 2-in. (51 mm) wide elastic bearing pads
of the joint. The other ends of floor slabs were temporarily su
crew jacks placed on concrete blocks as shown in Figs. 7 and 8.
esting, the screw jacks were replaced with load cells.

complete joint test, the grout in the joint extended about 3-
m) into the slab cores to provide continuity. This was accompli
ting crumpled newspapers as "dams" to stop the flow of grout b
red point. In tests where the slab cores were deliberatel
led, the cores were completely blocked at the face using duc
joint was then filled with grout.

wall panel above the joint rested on dry-packed mortar about
mm) thick. The mortar was packed from both sides of the wall
ly fill the joint.

Materials and Fabrication

.2.1 Floor Elements

Hollow-core slabs used in all series had a design compressive s
of 5000 psi (34.5 MPa). Cross-sectional dimensions are sh
Fig. 23.

.2.2 Wall Panels

Precast concrete wall panels were used. Top and bottom wall bloc
identical. A cross section is shown in Fig. 24.

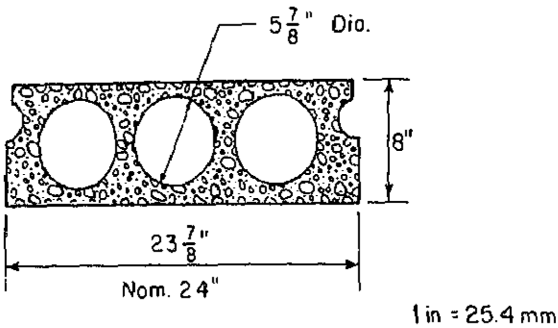


Fig. 23 Slab Cross Section

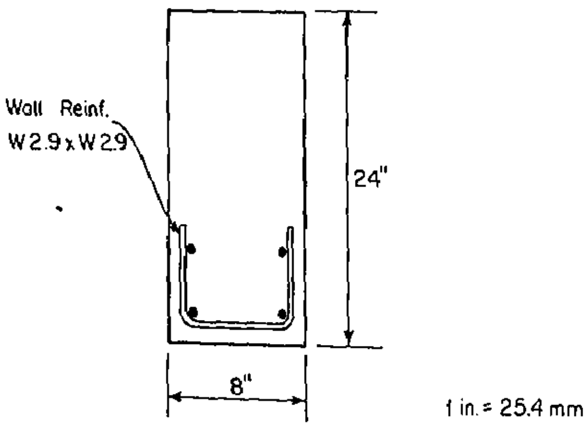


Fig. 24 Wall Cross Section

g Type I Portland Cement, Elgin Sand and Gravel with a maxi egate size of 3/4 in. (19 mm). The specimens and test cylind cured in the forms under plastic sheets for at least 3 days af ing. Compressive strength of concrete was determined from age of nine 6x12-in. (152x305 mm) cylinders prior to testing. Th es are given in Tables 2 and 3.

ome tests, both wall panels were reinforced at the ends with 6x6- xW2.9 reinforcement to limit splitting. The total amount forcement provided in each wall was 0.116 in.^{2} (75 mm^2).

3 Grout and Mortar

t strength was one of the major variables. Tests were made w t strengths of approximately 3000, 5000, and 7000 psi. (20.7, 3 48.3 MPa). Actual compressive strengths are listed in Tables 3.

ratory tests were made to determine the properties of fine aggreg fluid grout prior to starting the test program on full-scale jo imens. These tests are described in Appendix D.

t 1-in. (25.4 mm) thick dry-packed mortar was placed under the panel. The mixture contained equal parts by weight of Type nt and Elgin Sand, and just enough moisture to make it workab ial metallic packers were used to ensure proper packing of the m layer.

sed edges of grout and dry-packed mortar were covered with plas ts for at least 3 days curing after they were placed. Compress ngth of dry pack was usually higher than that of wall panels t in the joint. A strength of about 9000 psi (62.1 MPa), was ed from the average of six 2x2-in. (50x50 mm) cubes tested at an pproximately 5 days.

wall shortening and wall splitting. The layout of instrumentation interior joint test is illustrated in Fig. 25. Test setup for exte joints was similar. Due to the built-in eccentricity of the exterior jo the slab was also supported horizontally and the horizontal reaction measured.

C.3.1 Forces

In the case of Specimen JM-1 with long slabs, two sets of load cells(were used to measure the slab end reactions and the applied floor mom as shown in Fig. 5. The slab load was applied with hydraulic rams Force was measured by a pair of load cells placed between the top slab and the cross heads on both sides of the connection.

All other tests were conducted with short slabs. The support react were measured by two 25-kip (111 kN) load cells placed on conc blocks under the slabs.

C.3.2 Joint and Wall Shortening

Three 1-in. (25 mm) Linear Variable Differential Transfor (LVDT)[4] were used to measure shortening of the joint, upper panel and the lower wall panel over a length of about 10 in. (0.25 Also, in some tests, an extra LVDT and a strain gage were used on other side of the joint to measure shortening of the grout column alo

C.3.3 Wall Splitting

Two 0.001-in. (0.025 mm) dial gages were used to measure upper and l wall splitting. The gages were mounted to detect changes in wall th ness. Tensile strains were also sensed underneath the upper wall p by two 67-mm gage-length electrical strain gages[3] mounted as s in Fig. 25.

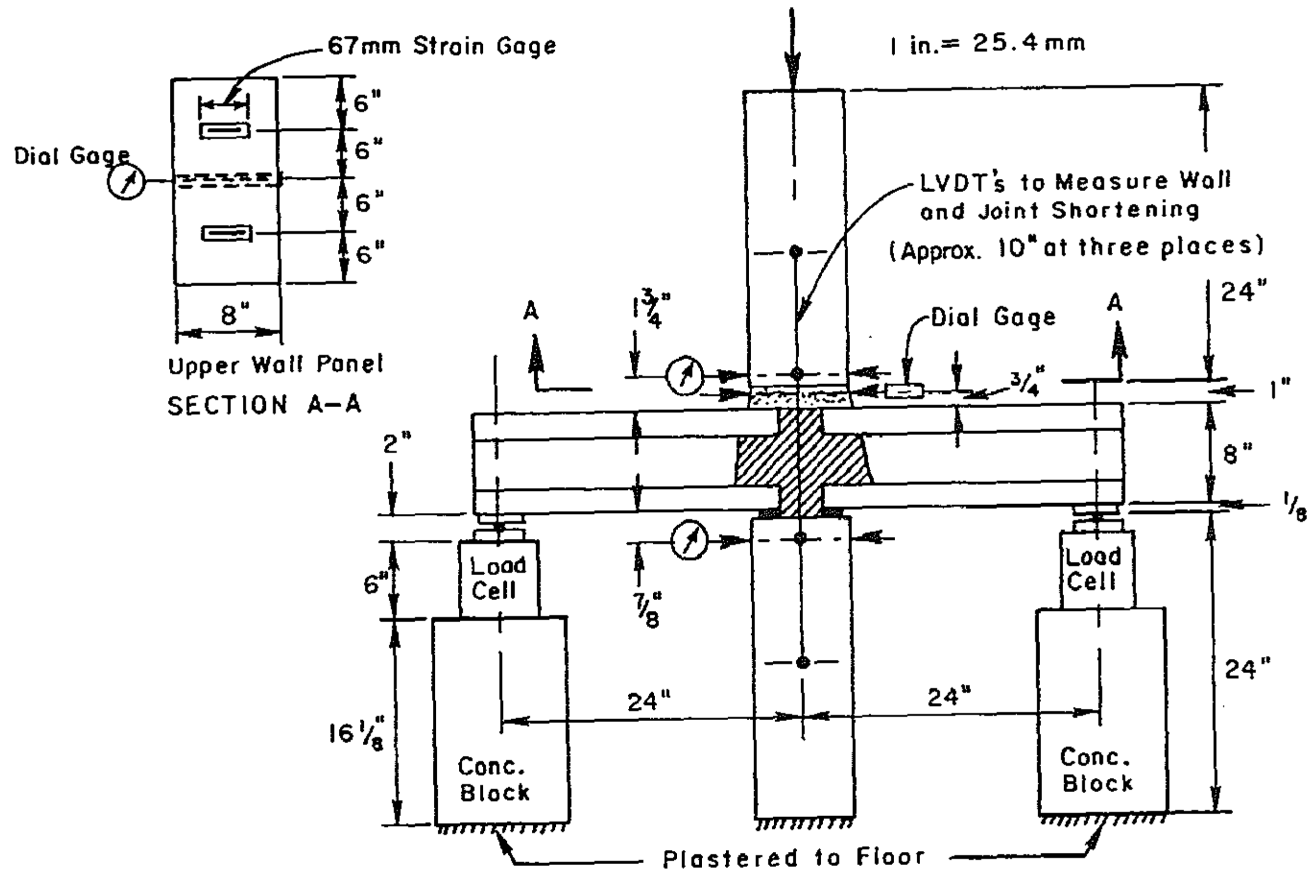


Fig. 25 Layout of Instrumentation for Interior Joint Test

All load cells, LVDT's and strain gages were connected to the Dig
Data Acquisition System (DDAS). A mini computer was interfaced
DDAS system to obtain simultaneously a magnetic tape record and prin
of raw data. The dial gages were recorded manually.

C.4 Test Procedure

Test setup and loading arrangement are shown in Figs. 7 and 8 for inte
and exterior joints, respectively. A 1,000,000 lb. (4448 kN) tes
machine was used to apply the vertical compressive force. Load was app
through a 1-in. (25.4 mm) thick steel plate plastered to the top of
upper wall panel. The specimen was centered below the loading head.

Specimens were loaded incrementally to destruction. The loading head of
machine was locked by inserting wedges after two or three load stages.

Each specimen was loaded in about 25 increments. The size of increment
reduced as the ultimate strength was approached.

After each load increment, measurements of all data were recorded. Cr
were identified and marked on the specimen in the order of their format
Any other characteristics that occurred in the specimen after the initia
of the cracks were recorded also. The maximum load sustained was consid
as the strength of the joint.

st Program

n objective of the tests was to determine the properties of
fill both longitudinal and transverse joints in LP structures.
e strengths were measured on 2-in. (51 mm) cubes, 2x4-in. (51x10
rs and 6x12-in. (152x305 mm) cylinders at 7 and 28 days. Te
ng tests were made on 2x4-in. (51x102 mm) cylinders at the same a

n variables included were:
Aggregate to cement ratio.
Water to cement ratio.

t program consisted of two series. Series A used an aggrega
ratio, by volume, of 3.0. Series B used a ratio of 2.25. For
the water to cement ratio, by weight, was varied from 0.37
Amounts of materials used for each batch of grout are shown in
nce there was always some free moisture present in aggregates
mate adjustment was made each time to the amount of water adde
.

TABLE 10 - GROUT CONSTITUENTS AND MIX WEIGHTS

Materials	Bulk Unit Weight lb./cu. ft.	Mix Weights, lb.	
		Series A	Series B
Type I Cement	94	40	40
Elgin Sand F.M. = 3.10	101	130	96
Water	62.4	Varied	Varied

Metric Equivalents: 1 lb. = 4.448N
1 cu. ft. = 0.02832 cu.m.

tively, Construction Engineer, Construction Methods Section
g Senior Structural Engineer, Structural Development Sec
d Cement Association, Old Orchard Road, Skokie, Illinois.

for about 48 hours after fabrication. The specimens were then demol
stored in the moist room until about two hours before testing. The
cylindrical specimens for compression tests were capped with high s
capping compound and the caps were allowed to cure at least one hou
to compression testing. The strengths of grout were determined f
average of at least four specimens.

D.2 Test Results

Average grout strength versus water-cement ratio are shown in F
through 29. Average values for each series are given in Table 11.

The tests indicated that when the grout was either too stiff or too
the results were inconsistent. When the water-cement ratio was lo
paction was a problem, and inconsistency resulted from a nonuniform
With high water-cement ratio, the mix was very fluid. Compaction
required. However, heavier particles tended to settle down leaving
layer of water on top. Also, the mix had to be constantly agitate
the specimens were being cast.

Based on these tests, it appears that the most appropriate water
ratio to achieve good workability and consistency would be in the r
0.5 to 0.75 with an aggregate-cement ratio of 3.0, and between 0.
0.625 for an aggregate-cement ratio of 2.25.

Tests were also made to determine the fineness modulus, moisture c
unit weight, and specific gravity of sand that was used as fine aggre
grout mix. The results of tests on fine aggregate are tabulated i
12. The gradation curve shown in Fig. 30, was plotted from the res
standard sieve analysis. The material conformed to the
requirements.(7)

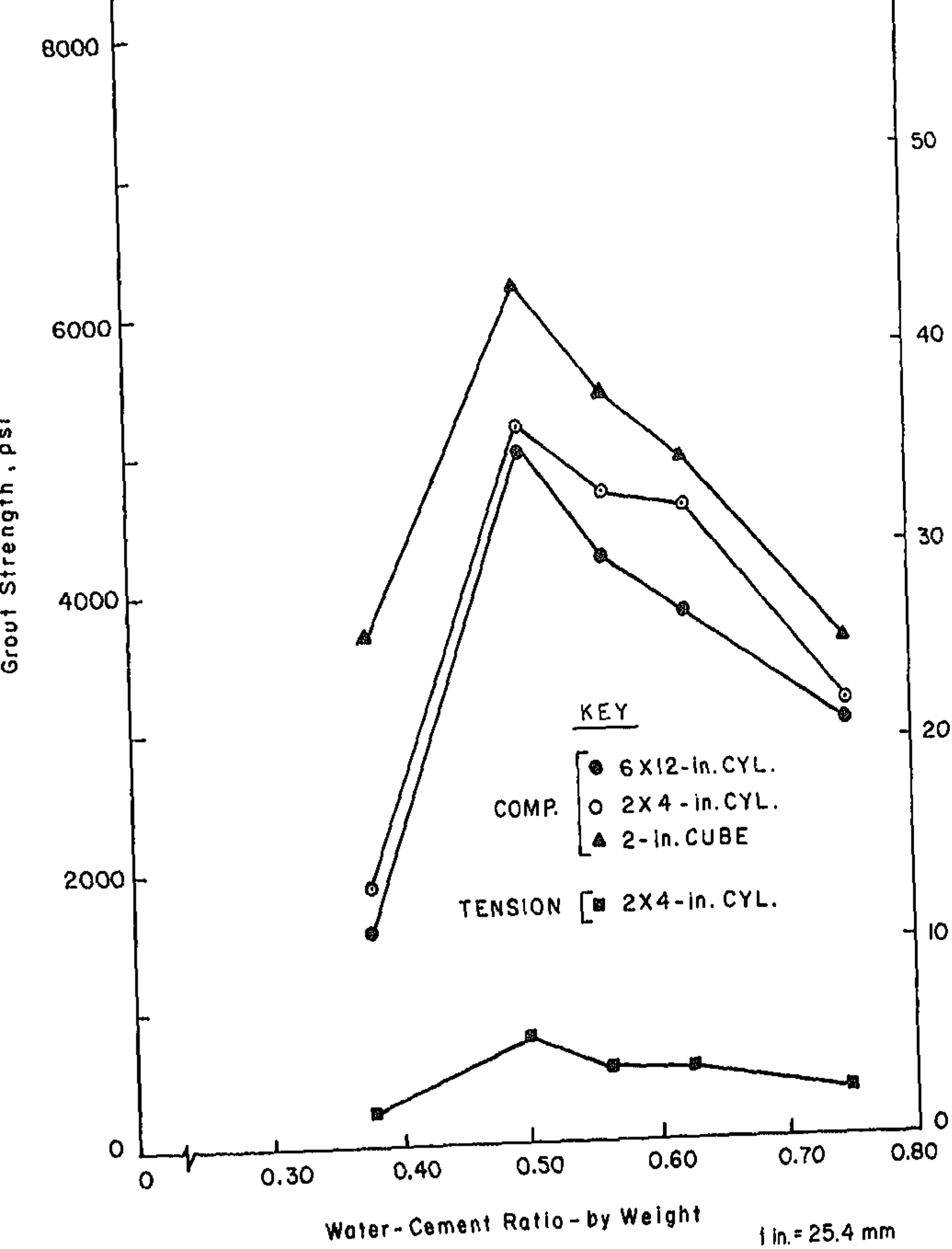


Fig. 26 Strength versus Water-Cement Ratio at 7 Days for Series A

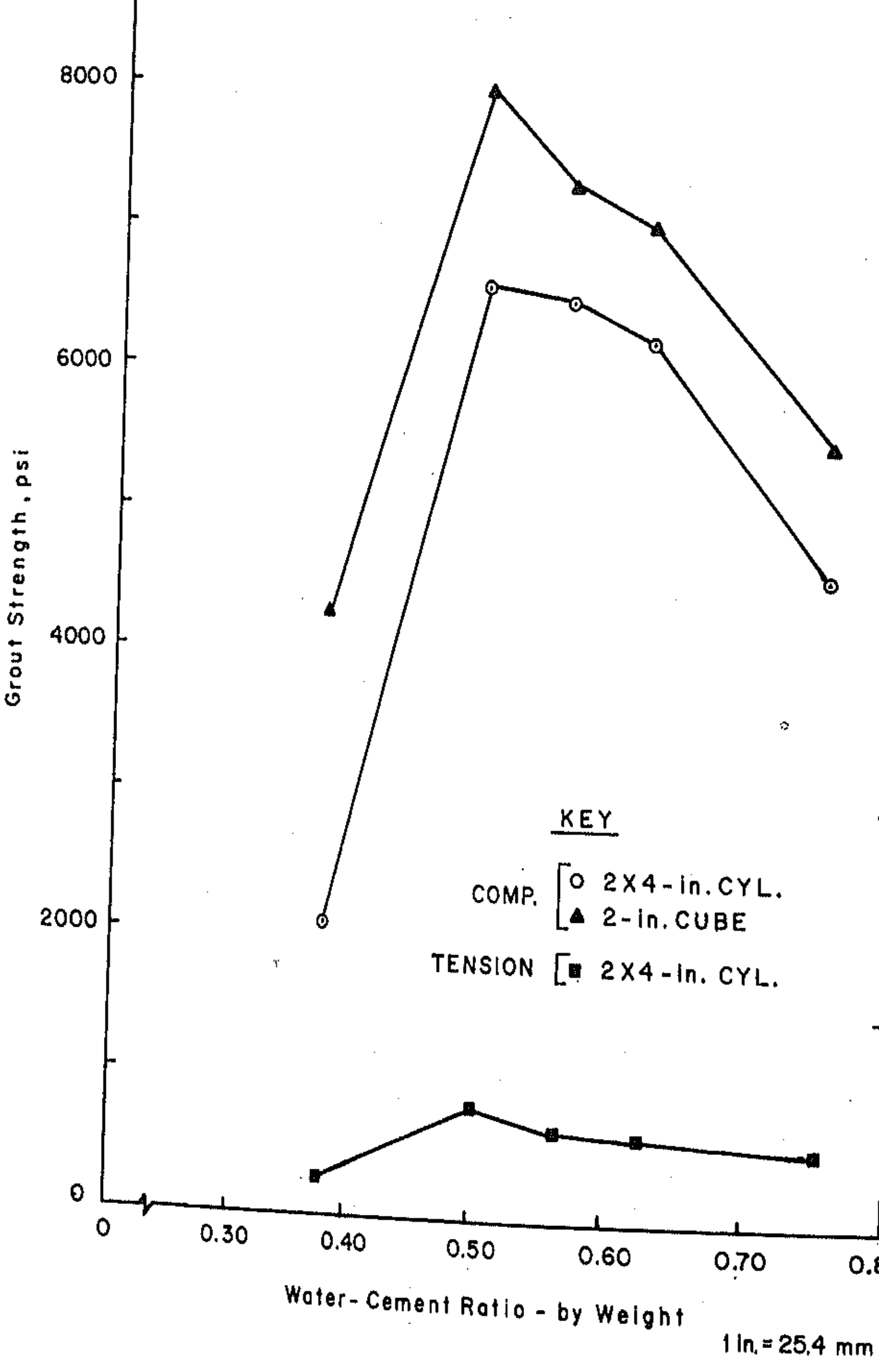


Fig. 27 Strength versus Water-Cement Ratio at 28 Days for Se

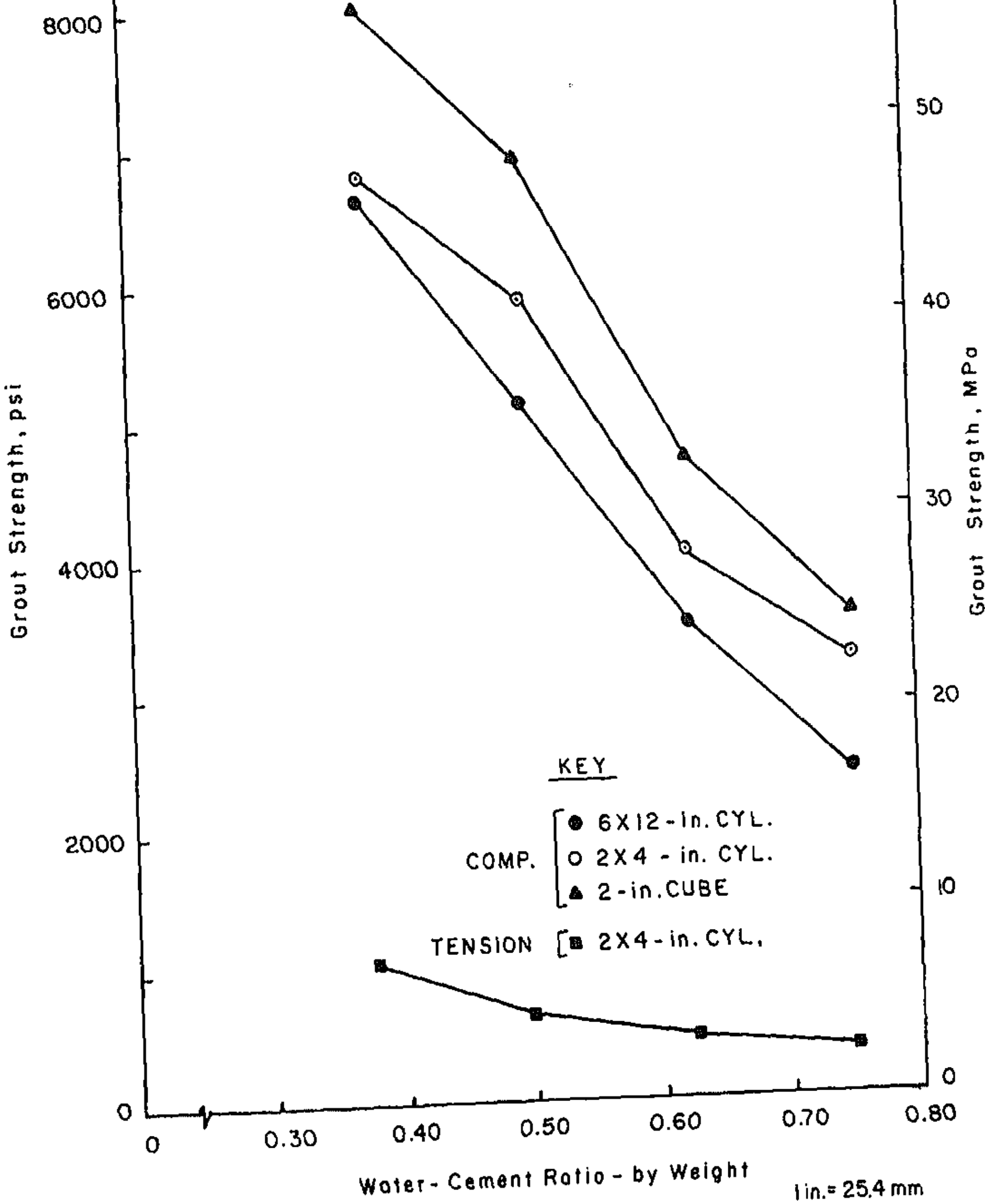


Fig. 28 Strength versus Water-Cement Ratio at 7 Days for Series B

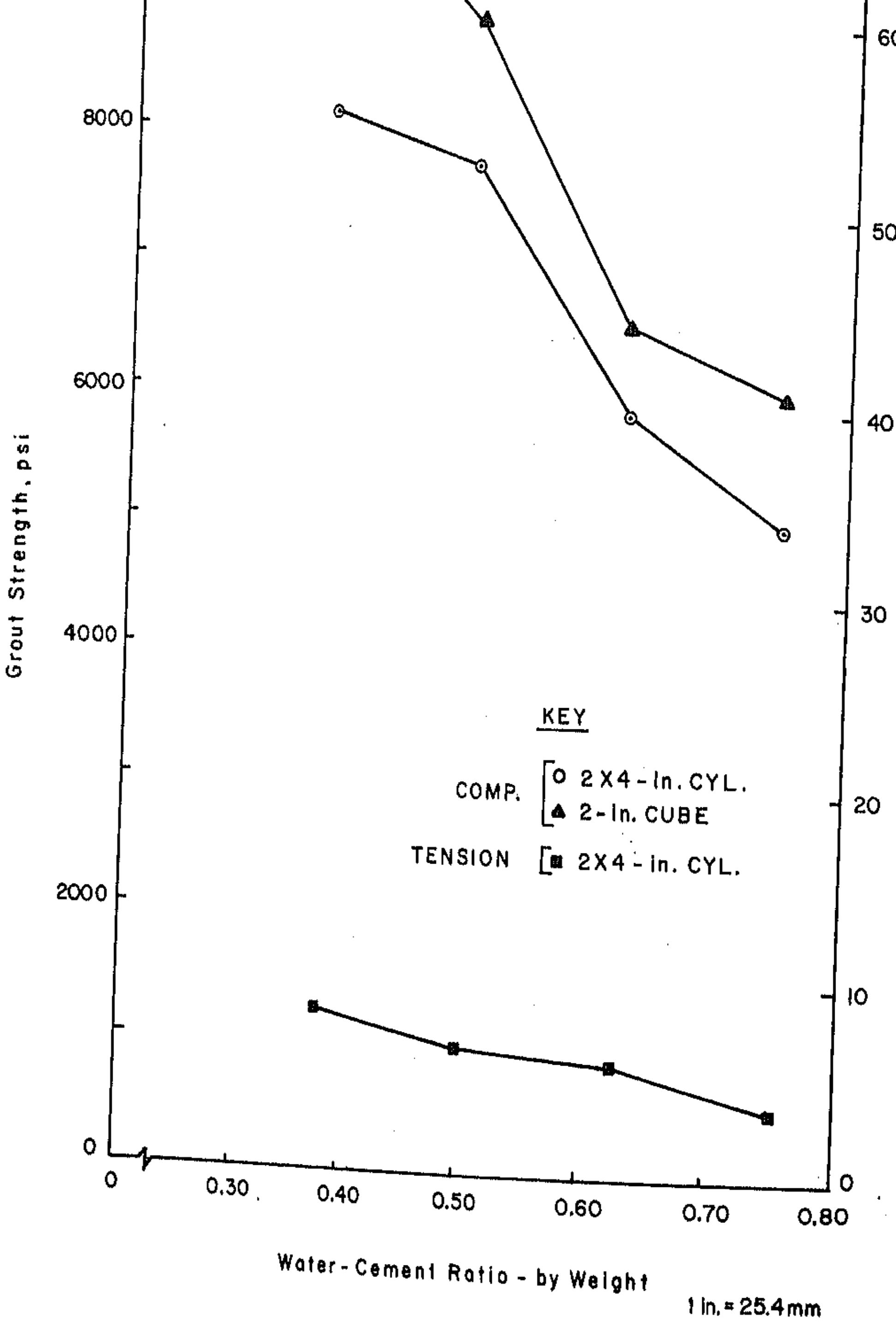


Fig. 29 Strength versus Water-Cement Ratio at 28 Days for Series E

Aggregate-Cement Ratio (by volume)	Water-Cement Ratio (by weight)	Average Compressive Strength* (psi)					Avg. Tensile Strength* (psi)	
		2-in. Cubes		2x4-in. Cyl.		6x12-in. Cyl.	2x4-in. Cyl.	
		7 Days	28 Days	7 Days	28 Days	7 Days	7 Days	28 Days
3.0	0.375	3700	4240	1880	2070	1550	250	270
	0.500	6220	7890	5190	6510	5040	770	800
	0.562	5490	7220	4720	6490	4250	530	650
	0.625	4990	6960	4610	6170	3880	510	620
	0.750	3610	5460	3180	4510	3060	360	540
2.25	0.375	8050	10000	6830	8050	6640	1040	1240
	0.500	6970	8750	5920	7660	5130	650	980
	0.625	4710	6410	4030	5790	3550	480	860
	0.750	3570	5900	3240	4940	2400	350	510

* Average strength of at least four specimens.

Fineness Modulus		3.10
Moisture Content		3.14 %
Specific Gravity		2.73
Unit Weight (pcf)	Natural	101
	Dry	115

Metric Equivalent: 1 pcf = 16.02 kg/cu.m

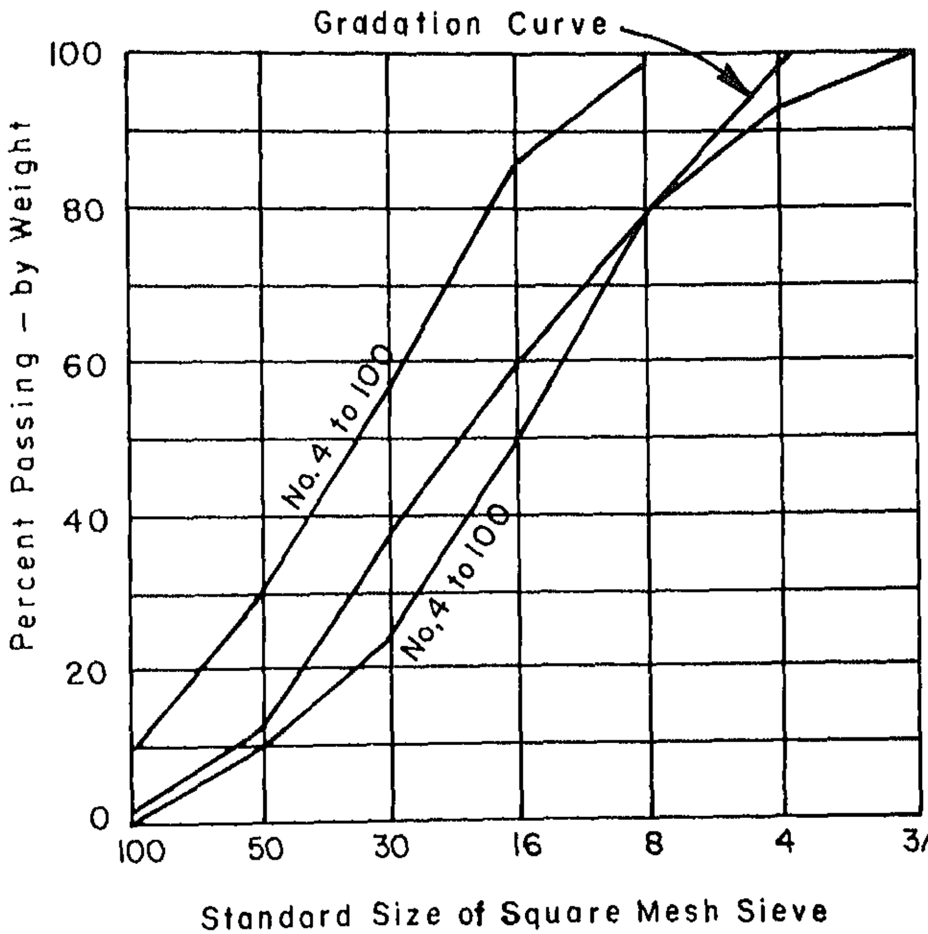


Fig. 30 Gradation Curve for Fine Aggregate

ACKNOWLEDGEMENTS

This investigation was carried out at the Structural Laboratory of land Cement Association under the direction of Dr. H. G. Russell Structural Development Section and Dr. W. G. Corley, Director, E Development Department. Particular credit is due B. Wm. Fullhart, Graves, for their assistance in the manufacture and testing of the and Wm. Hummerich, Jr. for instrumentation. Mr. M. Fintel, Advanced Engineering Services Department, Portland Cement Assoc overall project supervisor. Mr. D. M. Schultz, Senior Structural Structural Development Section contributed significant direction in design of the test specimens, conduct of the tests and interpr the data.

tel, M., Schultz, D.M., and Iqbal, M., "Report 2: Philosop
uctural Response to Normal and Abnormal Loading Conditions," D
Construction of Large Panel Concrete Structures, Office of
elopment and Research, Department of Housing and Urban Develo
hington, D.C., August 1976. Also PCA Publication EB92.

ultz, D.M., Johal, L.S., Derecho, A.T. and Iqbal, M., "Repo
cial Topics," Design and Construction of Large Panel Co
uctures, Office of Policy Development and Research, Departme
sing and Urban Development, Washington, D.C., January 1979. Als
lication EB95.

hestad, E., Hanson, N.W., Kriz, L.B., and Kurvits, O.A., "Faci
Test Methods of PCA Structural Laboratory," Journal of the Po
ent Association, Research and Development Laboratories, Vol. 1
37; Vol. 1, No. 3, 1959, pp. 35-41; PCA Development Bulletin D33.

son, N.W., Hsu, T.T.C., Kurvits, O.A., and Mattock, A.H., "Faci
Test Method of PCA Structural Laboratory - Improvements 196
rnal of the Portland Cement Association, Research and Devel
oratories, Vol. 3, No. 2, May 1961, pp. 27-31; Vol 7, No. 1, Ja
, pp. 2-9; and Vol. 7, No. 2, May 1965, pp. 24-38; PCA Devel
etin D91.

Committee on Precast Bearing Wall Buildings, "Consideration fo
gn of Precast Bearing Wall Buildings to Withstand Abnormal Lo
nal of the Prestressed Concrete Institute, Vol. 21. No. 2, M
l 1976.

construction and Construction Evaluation of Mortars for Plai
forced Unit Masonry," (C780-74) American Society for Testin
rials, Philadelphia, part 16, 1977, pp. 436-451.

ndard Specification for Concrete Aggregates," (C33-77) Ame
ety for Testing and Materials, Philadelphia, part 14, 1977,
14-17.

Canadian customary value by the conversion factor exactly ... For example, to convert 11.4 ft. to meters: 11
priate number of significant digits desired. ... for an accuracy of two significant digits. Do not round
3.47472 which rounds to 3.47 meters for an accuracy would be reduced. A complete guide to the
before performing the multiplication, as accuracy would be reduced. A complete guide to the
and its use can be found in ASTM E380, Standard Metric Practice Guide (A Guide to the Use of
International System of Units).

To convert from	to	multiply
Length		
inch (in.)	centimeter (cm.)	
inch (in.)	meter (m.)	
foot (ft.)	meter (m.)	
yard (yd.)	meter (m.)	
Area		
square foot (sq.ft.)	square meter (sq.m.)	
square inch (sq.in.)	square centimeter (sq.cm.)	
square inch (sq.in.)	square meter (sq.m.)	
square yard (sq.yd.)	square meter (sq.m.)	
Volume		
cubic inch (cu.in.)	cubic centimeter (cu.cm.)	
cubic inch (cu.in.)	cubic meter (cu.m.)	
cubic foot (cu.ft.)	cubic meter (cu.m.)	
cubic yard (cu.yd.)	cubic meter (cu.m.)	
gallon (gal.) Can. liquid**	liter	
gallon (gal.) Can. liquid**	cubic meter (cu.m.)	
gallon (gal.) U.S. liquid**	liter	
gallon (gal.) U.S. liquid**	cubic meter (cu.m.)	
Force		
kip	kilogram (kgf)	4
kip	newton (N)	4,4
pound (lb.)	kilogram (kgf)	
pound (lb.)	newton (N)	
Pressure or Stress		
kip per square inch (ksi)	kilogram per square centimeter (kg/sq.cm.)	
pound per square foot (psf)	kilogram per square meter (kg/sq.m.)	
pound (force) per square foot (psf)	pascal (Pa.)†	4
pound per square inch (psi)	kilogram per square centimeter (kg/sq.cm.)	
pound (force) per square inch (psi)	pascal (Pa.)†	6,89
Mass (Weight)		
pound (lb.) avdp.	kilogram (kg)	
ton, 2,000 lb.	kilogram (kg)	90
grain	kilogram (kg)	
Mass (weight) per Length		
kip per linear foot (klf)	kilogram per meter (kg/m.)	
pound per linear foot (plf)	kilogram per meter (kg/m.)	
Mass per Volume (Density)		
pound per cubic foot (pcf)	kilogram per cubic meter (kg/cu.m.)	1
pound per cubic yard (pcy)	kilogram per cubic meter (kg/cu.m.)	
Temperature		
degree Fahrenheit (deg. F.)	degree Celsius (C)	$t_C = (t_F$
degree Fahrenheit (deg. F.)	degree kelvin (K)	$t_K = (t_F$
Energy		
British thermal unit (Btu)	joule (J)	1,05
kilowatt-hour (kwh)	joule (J)	3,600,00
Power		
horsepower (hp) 550 ft.-lb./sec.	watt (W)	74
Velocity		
mile per hour (mph)	kilometer per hour	
mile per hour (mph)	meter per second (m./s.)	

*E indicates that the factor given is exact.
**One U.S. gallon equals 0.8327 Canadian gallon.
†A pascal equals 1.000 newton per square meter.